"ARCHITECTURAL AND ENVIRONMENTAL REVIEW OF THERMOCHROMIC CLADDING. CASE STUDY: WATES HOUSE"

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Abstract

This paper considers issues of sustainability, concerning energy saving in combination with aesthetics in energy efficient building design. It discusses the potentials of re-cladding an existing building in the centre of London, in order to improve its energy performance and CO_2 emissions. The case study building is Wates House, the home of the Bartlett Faculty of the Built Environment at UCL. The building's proposed façade is intended to play an active role by changing properties and reacting according to various climatic stimuli. The behaviour of the façade influences the environmental conditions of the interior space, in order to retain comfort levels for its occupants. The design –proposal for the external envelope of Wates House, will summarise an attempt to improve the overall energy performance of the building, as well as to enhance the aesthetic appearance reflecting the avant-garde technology implementations.

This simulation study compares different types of glass such as single and double glazing with Low-E coating and several options for its applicability are examined. Main interest though of this report is to investigate the potentials of one of the most highly performing glazing. The under-research glass material belongs to the category of glazing that are responsive to light and its characteristic is that it changes its properties (colour) according to the temperature of the external pane. Different surfaces of this material are tested as well, in order to evaluate which is the most appropriate for the case study building.

By careful design the goal is to maximize the use of solar radiation by optimizing the surface of the thermochromic; this is followed by a great decrease in electrical lighting consumption and reduce unwanted solar gains and possible glare to such an extent that mechanical heating and cooling is not significantly required to maintain comfort condition. Annual energy and peak demand impacts are also investigated. By means of software simulations it will be indicated that integrating this innovative cladding design, comfortable conditions are provided with far less energy consumption compared to air-conditioned offices, and a modern, exciting, aesthetic, energy efficient façade is created. Such an implementation may offer great benefits not only in the case study of Wates House but in general to public buildings of this kind.

Acknowledgments

...................I would like to take the opportunity to thank my supervisor Dr. Ben Croxford for his invaluable support, co-operation and advice throughout the whole period of the present dissertation.

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1. Introduction

Buildings play a significant role in the global energy balance. They account for 20-30% of the total primary energy requirements and they are responsible for a great percentage of carbon emissions[3]. "The facade of a modern building is one of the most expensive and important element of building construction and can represent up to 35% of construction costs; it represents the manifestation of the architect's expectation of the external appearance of a building, and is the primary environmental modifier.

After the oil crisis in the 1970s and the manifestation of the Kyoto protocol there was an increased interest on energy conservation and in order to achieve it, passive and active means had to be incorporated in the building construction process. Most attention was given thereafter on the building's envelope that acts as an environmental sponge by filtering the external climatic conditions and sheltering the interior space. Its envelope is the single greatest controller of a building's interior environment in terms of light, heat and sound. It has been discussed that "*the building shell is analogous with our own skin, which is a waterproof, vapour transmitting, sensitive membrane containing signal transmitting nerve endings and heating and cooling systems all within a few millimetres of its surface*"[4]. With the appropriate use of materials and analogies of voids and solids, the building may have the ability to actively modify energy flows through its envelope, by regulation, enhancement, attenuation, rejection or entrapment[5].

The basic concept in terms of energy matters was to approach the philosophy of an intelligent building that is based significantly on the performance of its envelope-façade. Such a façade may allow ventilation and natural light to enter. It can incorporate solar shading, noise attenuation, insulation against heat loss and heat gain, and collect solar power for electricity generation. The most commonly material used for its construction in recent years is glass. Since it became more as a symbol rather as a construction material many advances have been made in glass technology in order to improve its physical characteristics and performance in terms of energy consumption. The implementation of such a façade structure would provide the ability to adjust itself automatically and offer optimum internal comfort by self-regulated amendments to the building fabric with the minimum use of energy.

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[3] Andrea Compagno, Intelligent Glass Facades, Material Practice Design, Birkhauser, 1995, Germany, p. 5

[4] http://www.tech.plym.ac.uk/soa/arch/intel1.htm

[5] ibid

New technologies can range from double or triple glass with Low-E coating and spectrally selective types with very low U-values, to photovoltaic elements and the application of the most efficient 'smart' and 'adaptive' glazing components that are designed to meet a specific need[6]. The intelligent façade system selected and proposed in this report is thermochromic glazing.

1.1 Aims and objectives of the study

This study aims to investigate options for high technology dynamic facades, using as a case study one of the buildings at UCL, Wates House where the undergraduate part of the faculty of the Built Environment, the Bartlett is based. More specifically it deals with the retrofitting of a modern glazing structure onto an existing building. In its role as a transparent façade system, the glazing structure must perform a wide range of "functions," which in turn challenge a wide range of performance criteria that all have to follow the guidelines for sustainable design. In this report there is a clear focus on the subset of those architectural criteria related to comfort, view, daylight and energy use. Additional critical performance issues such as structural, acoustics are not extensively addressed here, although in any given building application they may be critically important performance factors.

To achieve its aim, a cladding unit was designed that repeats itself and enwraps the whole buildings structure. The main target of this design is to eliminate the need for an air-conditioning system by incorporating the maximum use of solar energy and daylight, while controlling solar gain and reducing overheating. A modular concept is adopted for the cladding unit to solve the technical challenges of integration and operation of the cladding in a wider context of commercial buildings.

[6] Michelle Addington and Daniel Schodek, Smart Materials and Technologies, for the architecture and design professions, Architectural Press, p. 3

1.2 A Brief History of the Bartlett

The Bartlett School of Architecture, Building, Environmental Design and Planning is the unique department of UCL that is devoted to the study and design of the built environment. With the ability to combine the disciplines of Architecture, Building, Environmental Design and Planning, the Bartlett is at the forefront of the debate that is shaping the future of our cities.

The School, named after its original benefactor Sir Herbert Bartlett, is housed in three buildings[9]. These buildings accommodate design studios and student working areas, computing and laboratory facilities and workshops. An extensive library contains books and periodical subscriptions on architecture, building, planning and environmental design. The Bartlett focuses on the full range of issues which concern the future fabric of cities, and uses London as a unique laboratory for studying the architectural, constructional and urban situations that affect the built environment[10].

Primary concern of this study is the building called Wates House. A small research study has been conducted over various aspects of the specific building, including its history, its geographical position and its construction elements, in order to proceed to the re-cladding process. Wates House is a relatively new building as it was opened in 1975 by Sir Ronald Wates to house the Bartlett School of Architecture and Planning. It is home to the Bartlett School of Bartlett School of Architecture, Building, Environmental Design and Planning, which name was changed in 1992 to the Faculty of the Built Environment, or more commonly 'The Bartlett'.[11] The buildings architecture expressed that époque's rural movement; straight lines, clear, rectangular shape with a ground plan that is easily readable. It is a heavy weight construction, representative of London's construction techniques and tendencies, forming a distinct-symmetrical grid of openings around the perimeter of the building.

1.2.1 Current Situation

With the evolution of the years and the progress of architectural styles, the design of Wates House does not reflect the current modern architectural profile within the Bartlett. The building has plenty of problems, including overheating in summer unless the windows are opened, when traffic noise becomes a problem. The use of single

[9] http://www.ucl.ac.uk/museumstudies/websites05/huang/album/pages/WatesHouse1.htm
[10] www.ucl.ac.uk/
[11] ibid

glazing in large areas results in draughts and can be cold in winter. A proposal for refurbishment is under consideration by the main college.

The current building was designed according to the legislations and specifications of another period; hence its performance and energy efficiency is poor for this building.

Climate change is affecting the UK climate and winters are predicted to become milder and wetter, with summers getting warmer. The buildings heavy weight construction met the seasonal requirements, especially during summer months when natural ventilation was adequate to decrease internal temperatures, with increasing summer temperatures and the problems of external noise, natural ventilation needs to be more carefully designed to work in this situation.

According to these demands UCL has introduced some buildings that not only reveal a current and modern approach in design, but indicate as well the tendency that the School has towards local climate and environment the last years[12]. In terms of this renewed policy Bartlett intends to apply environmental science to the efficient and healthy design and operation of buildings and cities. Wates House is clearly in need of refurbishment and some problems through its re-design need to be confronted. Such problems that occur are:

- How to design, maintain and operate the built environment while minimising the emissions of greenhouse gases.
- How to adapt the environment, fabric and services of existing and new building to climate change.
- How to improve the environment in and around the building to provide better health, comfort, security and productivity.

The need to enhance an environmental policy and management in all of the buildings, is emergent, since they represent part of the University's theory and notion and they have to be part of it. The aesthetic part has to be renewed as well and follow the new trends and avant-garde design manifestations made, in order to act as an advertisement for the architectural department and enhance its status in the wider field of architecture.

In this report it is estimated that such problems can be eliminated by careful design of an innovative-energy, efficient re-cladding of the building of Wates House by introducing new technologies that can efficiently reduce the energy consumption of the building while being cost effective. Simultaneously, a main concern is to integrate principles of vernacular architecture with the use of modern building materials and

[12] www.ucl.ac.uk/environment-institute

controls, in order to create a building skin that possesses the ability to act as a climate filter or moderator, by accepting and rejecting free energy from the external environment depending on seasonal and diurnal variations.

This research was initially driven by a wish to discover more about this emerging genre of building envelope design: characterised as 'the intelligent facade' by many authors and practitioners. In particular, my interest was focused on the workings behind intelligent façade systems such as advanced technology glazing. In parallel, natural ventilation was also considered for better control, while improved construction materials were proposed that can provide a better and more air-tight building structure.

1.3 UK Building Regulation

In order to achieve the above mentioned goals it is important to know the effect of buildings on energy use and carbon dioxide emissions. The UK is responsible for about 3% of global CO2 emissions and is aiming to achieve the Kyoto agreement targets by several means including setting building regulations[13]. These are designed to improve energy performance of buildings.

According to Thomas and Fordham (2005), in the UK about 45-50% of delivered energy use and just fewer than 50% of all CO2 emission is accounted for by buildings. Approximately 60% of building related energy consumption is due to the domestic sector and about 30% is attributed to the service sector (i.e. UK public and commercial buildings). In the service sector the total CO2 emission is about 89 million tonnes and approximately 44% of this is due to space heating. Table 1.1 presents CO2 emission of each end use in UK service sector.

Use of fuel	%
Space heating	44
Water heating	7
Lighting	17
Cooking	6
Air conditioning	6
Refrigeration	7
Power	13

Table 1. 1: Carbon dioxide emissions by end use for the UK service sector (Thomas and Fordham 2006, p.30)

[13] 'Action today to protect Tomorrow', The Mayor's Climate Change Action Plan, Greater London Authority, 2007

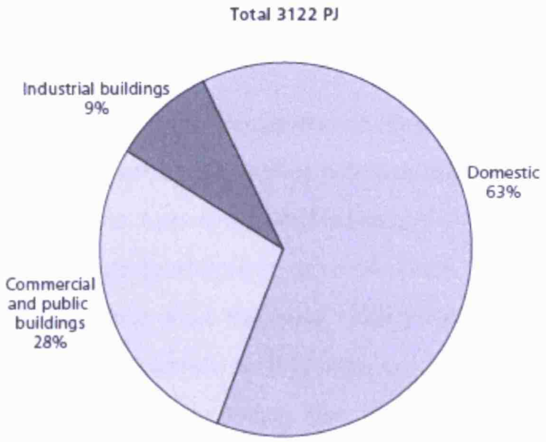

Figure 1. 1: Total UK delivered energy consumption by buildings in 2000. Source: Cibse Guide F, p.1-2

1.3.1 London's contribution to climate change

According to findings of the Climate Change Action Plan[14], UK is the world's eighth largest emitter of carbon dioxide. London is responsible for eight per cent of UK emissions, producing 44 million tonnes of CO2 each year. Unless action is taken, emissions are set to increase substantially. Given London's forecast economic and population growth, London's emissions are projected to increase by 15 per cent to 51 million tonnes by 2025.

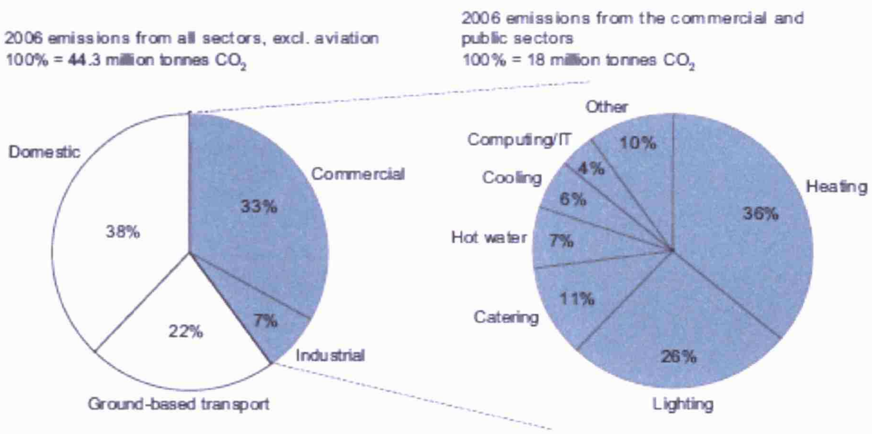

Figure 1. 2: 2006 CO2 emissions from London's commercial and public sector. Source : London Energy and CO2 Emissions Inventory; Defra

Emissions from the commercial and public sector are 15 million tonnes of CO_2 annually. These come primarily from electricity usage, including for lighting and computing, although as the climate continues to warm, energy used for cooling buildings could become increasingly significant.

[14] London Energy and CO2 Emissions Inventory; Defra

2.0 Building Regulations for refurbishment

According to the Document of Energy Efficiency of Cibse Guide F[15], a complete refurbishment of a building will normally require the whole design to meet the Building Regulations Approved Document L (9)[16]. Where windows, doors, heating, hot water, lighting, air conditioning or mechanical ventilation systems are replaced as part of a refurbishment then the new controlled service or fitting must meet Part L(9) of the Building Regulations as if it were a new installation.

In particular, considering the renovation of the building's envelope, the Approved Document L provides standard values for each thermal element that is going to be replaced. Furthermore, it provides a number of limitations for the U-Values that can be used for building components. These standards and limitation are summarized in the following tables.

Element	Standard for new thermal elements	Standard for replacement thermal elements
Wall	0.30	0.35
Flat roof or roof with integral insulation	0.20	0.20
Floors	0.22	0.25

Table 2. 1: Standards for thermal elements (W/m²K), Source: Building Regulations Approved Document L (9), p.21

Element	a. Area-weighted average U-value	b. Limiting U-value
wall	0.35	0.70
Flat roof or roof with integral insulation	0.25	0.70
Floors	0.25	0.55
Windows roof windows, rooflights and doors	2.2	3.3

Table 2. 2: Limiting U-value standards (W/m²K), Source: Building Regulations Approved Document L 2A), p.17

[15] Cibse Guide F, Energy Efficiency in Buildings 2004, p. 16-1

[16] The Buildings Regulation 2000 Approved Document Part L2 A, Conservation of fuel and Power in new buildings other than dwellings, p. 17

2.1. Designing for comfort

In the following section the recommended criteria in order to achieve a balanced and comfortable indoor environment are described and according to which the proposed re-cladding will be considered and designed. At this point it has to be mentioned that the comfort criteria were based on the fact that the building at present is hosting a library section (fifth floor), while the rest is comprised mainly by office spaces and according to these the design will take place.

2.1.1. Heating

The Fuel and Electricity (Heating) (Control) Order 1974(24) and the Fuel and Electricity (Heating) (Control) (Amendment) Order 1980 prohibit the use of fuels or electricity to heat premises above 19 °C[17]. This restriction does not mean that the temperature in buildings must be kept below 19 °C but only that fuel or electricity must not be used to raise the temperature above this level. According to the comfort criteria suggested in Cibse Guide A, for some applications, the recommended winter design temperatures exceed 19 °C. In these cases, it is explained that the recommended temperatures can be maintained by contributions from heat sources other than the heating system. These may include solar radiation, heat gains from lighting, equipment and machinery and heat gains from the occupants themselves. For the case study, according to the recommendations of table 1.5 in CIBSE Guide A (Appendix A1), the winter temperatures for offices is 21-23, while for libraries the temperature ranges according to the requirements of lending or reading zones (Appendix A1).

2.1.2. Cooling

Summer comfort conditions given in Cibse Guide A suggest that for the case of Libraries the acceptable temperature may vary according to the activity occurring in the building. Therefore, for lending would be 21-23, whereas for reading is 24-25 and for offices 22-24. These figures though can be more flexible when it comes to non air-conditioning buildings, since the tolerance of the occupants in this case is greater.

[17] Cibse Guide A, Environmental Design, p. 1.8

The indoor temperature though, should not rise more than 28°C, because this would result in dissatisfaction for many occupants[18].

2.1.3. Ventilation

The principle role of ventilation is to provide an appropriate level of indoor air quality (IAQ) by removing and diluting airborne contaminants. It is the process by which fresh air is supplied to the occupants and which is used to passively cool a space or as a mechanism to distribute the conditioned air to a space from a plant.[19] The ventilation of a building can be either achieved by means of natural ventilation or by mechanical plant. When designing with natural ventilation, from an energy perspective according to Cibse Guide F[20], the running costs are lower due to lower energy consumption, the maintenance cost is decreased and furthermore the capital cost diminishes.

The whole-building ventilation rate recommended by both the 2005 edition of CIBSE Guide A[21] is 10 litre·s–1 per person. This is based on the correlation between ventilation rates and health. Since naturally ventilated buildings cannot provide a constant ventilation rate, it is necessary to demonstrate that an equivalent level of air quality has been provided. This can be done by introducing mechanical systems that can be combined with the natural mode.

2.1.4 Lighting Design

A very important parameter that has to be considered in depth is the design of the lighting of the interior space of the re-cladded building. This is mainly affected by the design of the windows that, apart from their main role to provide light to enable a building to function, they also provide the view and a natural ventilation possibility. The best guidance according to Thomas and Fordham recommendations is probably to assume that daylight should be maximised subject to the constraint of glare, increased solar gains and possible greater heat loss. This means that daylight factors should be as high as possible, without causing glare though and minimize the need for electrical lighting, and therefore reduce cost.

[18] Cibse Guide A, Environmental Design, p. 1.12
[19] Cibse Guide A, Environmental Design, p. 4.2
[20] Cibse Guide F, Energy Efficiency in Buildings, 2004,
[21] Cibse Guide A, Environmental Design, p. 5-8

The Lighting Guide (CIBSE 1999), suggests that a daylight factor of 5% is adequate to provide the necessary lighting in a working space[22]. When natural light isn't sufficient then electrical lighting should supplement the need for light. The recommended lighting levels that should be achieved for the needs of the case study building are summarized in the following table:

Space	***Standard maintained illuminance (lux)***
Libraries, reading areas	500
Offices	
-filing, copying, etc.	300
-writing, typing, etc.	500

Table 2. 3: Recommended lighting levels illuminance (lux) (Thomas and Fordham 2005, p.97)

[22] Cibse Lighting Guide LG10, Daylighting and window design, 1999

3. New Façade Technologies

Apart from the strategies already mentioned, there are also a number of active supplementary techniques that can assist in reducing the energy consumption and thus the carbon emissions of a building. Such techniques are the emergent technologies of advanced glazing systems that are introduced lately in the building construction sector in order to improve the buildings overall performance and such systems are going to be described in the following sections.

From an energy and environment viewpoint, it is well understood that the glazed component of a building is at the same time, the weakest and the strongest element. Its disadvantages are associated with heat loss, thermal and visual discomfort, while its benefits include passive solar heat gain, electric lighting power reduction, and view. Advances in technology have significantly improved its overall performance that is characterized by U-value, Solar heat gain coefficient (SHGC) and visible transmittance, transforming well designed glazing into a fundamental contributor for energy savings in buildings. During the last 15 years, low emissivity (low-e) glazings and other improvements in window technology have significantly reduced window-related energy use and peak demand in residential and commercial buildings.

At this point it is important to analyse the way that these types of windows function, in order to comprehend their contribution in energy saving philosophy. By reflecting long-wave radiant energy, low-emissivity (or low-e) windows reduce its U-value and therefore decrease heat loss through the windows. Although valuable in all climates, reduced U-values are most useful in colder climates where heating energy requirements are significant[23] and is mostly important for this paper, due to London's climatic characteristics. Most Low-e coatings are usually tuned to reflect the far infrared radiation, allowing only the visible part of the spectrum to penetrate the window. Such systems provide high solar gains during the heating season thus offsetting heating loads, while during summer they block the excess heat and allow only light to enter (Figure 3.1). Such coatings when they are combined with gases in the interior space with low thermal conductivity, then they can lower significantly the U-value of the window (Fig. 3.2). The most effective gases are those in the argon series, which have low thermal conductivity and little tendency to convert. In a Low- E double glazed unit in which air is replaced by argon, the U-value is typically reduced from 1.8 W/m^2 K to 1.5 W/m^2 K[24].

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[23] Apte Joshua, 'Future Advanced Windows for Zero-Energy Homes', ASHRAE, p.2

[24] Notes on seminars of EDE course, Building Solar Design.

Figure 3.1 presents a comparison; in the visible part of the spectrum the reflectance curves are close, diverging at 1600 nm, whereas, in the far infrared the Low-E coating has a high reflectance.

Figure 3.2 shows the reduction in U-values of sealed double and triple Low-E glazed units when gases with lower conductivity than air occupy the inner space.

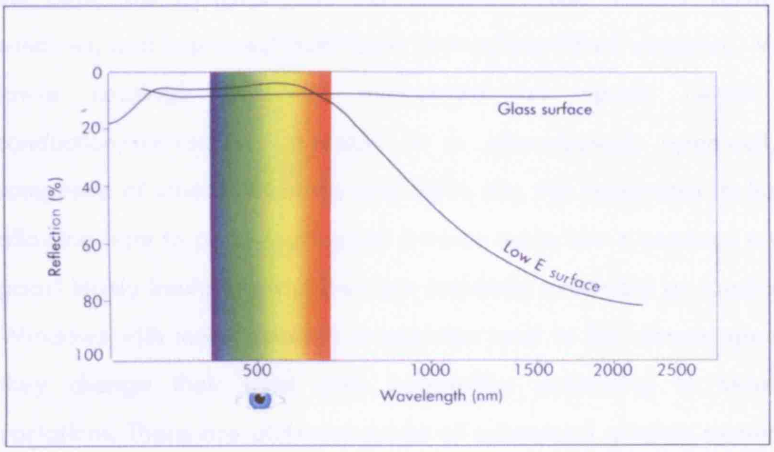

Figure 3. 1:Spectral reflectance properties of Low-E and clear glass. Source: Button and Pye 1993

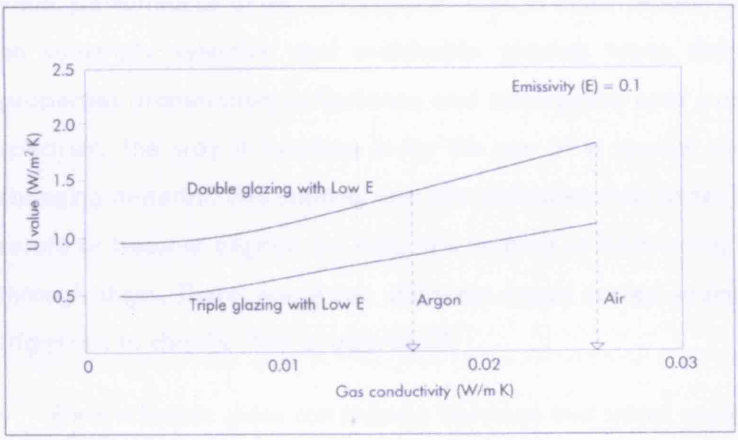

Figure 3. 2: Influence of gas conductivity on glazing U-values. Source: Button and Pye 1993

A new generation of highly efficient ("super")[25] window that require advanced technological systems and can be retrofitted in the building envelope are examined in this chapter and the type of cladding for the case study building is selected.[26]

[25] Apte Joshua, 'Future Advanced Windows for Zero-Energy Homes', ASHRAE, p.1

[26] http://www.tech.plym.ac.uk/soa/arch/intel1.htm

3.2 Glazing Types

Another type of façade technology is the emerging "smart" glazing. These technologies are currently in research and are expected to lay the groundwork for the next generation of residential window products (Carmody et al. 2000; Arasteh 1995). Several types of advanced glazing are currently being researched in order to reduce the heat loss (U-factor) of the window. These include vacuum windows, aerogel windows, and improved multi-layer low-e/gas-filled windows. Vacuum windows utilize low-e coatings and an evacuated air space (which virtually eliminates conduction/convection). Aerogel is a silica-based, open-cell, foam-like material composed of about 4% silica and 96% air; this maximizes its insulating value, but still allowing light to pass. Multi-layer (two or more low-e coatings and gas-filled insulating gaps) highly insulating windows are currently available as specialty products.[27]

Windows with more dynamic properties tend to be climate-specific, which means that they change their heat gain properties according to seasonal or temperature variations. There are different types of advanced glazing systems which are designed to maximize the energy-saving potential of daylighting, while improving comfort and visual performance at an "affordable" cost. In these reports the interest is concentrated on spectrally selective and switchable glazing types that can alter their optical properties (transmission, reflectance and absorption) over parts of the electromagnetic spectrum. The way it functions is by the use of a special coating which is the phase changing material. This coating contains molecules that under an external influence can rotate or become aligned (or not), thus helping or obstructing the passage of radiation through them. There are three different types sorted mainly by the way they are triggered to change their properties[28]:

- Electrochromic glass can change between two states under the effect of an electric field. Some types need power only during changing while others require a constant field to remain in one state. Visible transmittance dynamic ranges of 5% to 60% are achievable, with associated changes in solar heat gain coefficient, of 10% to 45%. Such coatings may be designed to switch to even lower transmittance levels which may be desirable to improve privacy, but this is obtained with some sacrifice in other performance properties (Reilly et al. 1989).

27 Apte Joshua, 'Future Advanced Windows for Zero-Energy Homes', ASHRAE, p.1

28 Advanced Fenestration Systems for Improved Daylight Performance, *Daylighting '98 Conference Proceedings*, May 11-13, 1998, Ottawa, Ontario, Canada

- Photochromic glass can change and become darker under sun radiation. It has found application in sunglasses that are lighter inside an enclosed space but become darker when the person goes out in the sunlight. At present they are still uneconomical for general applications. They are suitable for glare control, but not as much for solar heat gain as they tend to reduce only the visible portion of the spectrum.
- Thermochromic glass can change properties in response to changes in ambient temperature. As they get warmer they change from clear to diffusing, dark and reflective[29].

According to research from the Department of Building Technologies, University of California, an important feature of those glazing types is that they are easily linked to an automated lighting control system in order to provide desired interior illuminance over a wide range of exterior lighting conditions. A daylight photosensor controls the interior electric lighting while additional sensors can be added to control the switching state of the switchable devices (in the case of electrochromic glazing). The control logic for such a switching glazing system may include some of the following parameters: glare control, maintaining the desired illuminance and view control, while the primary advantage is the ability to integrate them with an automated system to provide continuous control over the luminous environment.[30]

The applicability of each type of glazing is a function of the particular application. For the specific case study it was chosen to retrofit thermochromic application, since it was evaluated as having the required dynamic aesthetic appearance and also is potentially the most efficient choice.

Its applicability on large surfaces, and the advantages that it provides over electrochromic or photochromic glazings, which are still uneconomical to use in a wide range, constitutes it as a potential substitute of the double and triple glazing types that are currently in a wide use in the market. Electrochromic glass, contrary to the thermochromic, requires an electrical current to function, while photochromic is suitable for glare control, but not as much for solar heat gain as they tend to reduce only the visible portion of the spectrum.

[29] www.bfrc.org/Technical_Publications-Thermal_definitions.htm

[30] Selkowitz S., Lee E.S., Advanced Fenestration Sustems for Improved Daylight Performance, Building Technologies Department, University of California, 1998

3.2.1 Thermochromic glazing

Thermochromic glazing in windows has a great advantage in reducing energy consumption compared to other energy-saving glazing because it blocks near infra-red solar transmittance (most of heat from the sun comes in these wavelengths) in summer and allows it in winter (Selkowiz et al. 1988)[31].

The material that displays thermochromic abilities is VO_2 (Vanadium dioxide) and this due to change in its molecular structure. VO_2 coating has a switching temperature of 68°C, but when doped with different elements then this temperature can range according to the properties of each element. The findings of these experiments showed that different proportions of the dopant as well as different thicknesses of the deposited film produce coatings with different switching temperatures as well as different optical properties[32].

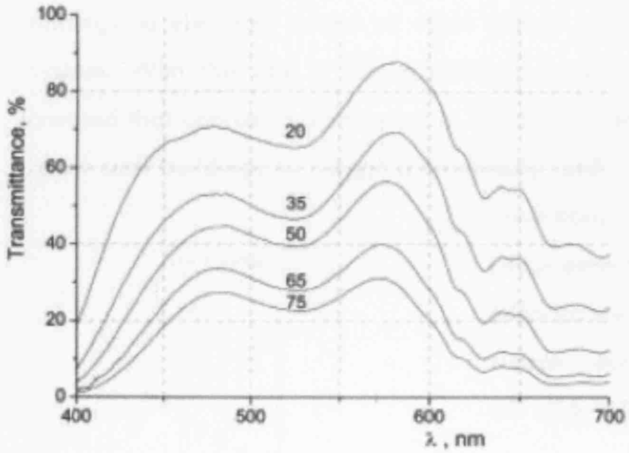

Figure 3. 3: Temperature dependent visible spectra of TLG interlayer of neutral type in the wave-length range 400-700nm. (Source: R.E. Arutjunjan, et al)

[31] Selkowiz S.E., Lampert C.M., Large Area Chromogenics: Materials and device for transmittance control, Vol. IS4, SPIE (1988) 22–44.

[32] Vernardou D., 2005. *The growth of thermochromic vanadium dioxide films by chemical vapour deposition.* Thesis (PhD). University of Salford

An important advantage of this thermochromic laminated glazing (TLG) is that it enables the automatic regulation of daylight by adapting dynamically to the continuously changing climatic conditions, aiding in that way in reducing the energy needs of a building and in providing thermal comfort. Neither electrical power nor driving unit is required.

In combination with Low-E glass, TLG makes possible to create a heating control for "zero net energy" buildings ("intelligent facades")[33]. The new developed type of laminated glass comprises a glass pane with thermochromic interlayer and a second glass pane, while in between a polymeric interlayer is placed that is doped with different kind of transition metals (fig. 3.4). This composition enables the glazing to act as a filter and react according to incident light (fig. 3.5). Energy modelling of the heat-transfer in ventilated facades has shown in a research made by the Technological University of Plant Polymers in Russia (TUPP), that TLG can provide decrease of 15-30% in the building energy consumption during the winter heating time. During summer time the reduction of solar energy gain reaches 30-40% and it is enough to get rid of air-conditioning at all.[34]

Thermochromic laminated glazing (TLG) developed in TUPP is a "smart" glazing that: '*regulates the entry of light on a programmable and automatic basis*'. According to their findings no electrical power or other power is needed to operate the thermochromic system. With the use of thermochromic material 'intelligent' window facades are created that can be implemented in buildings with extensive glazing. These techniques allow such buildings to adapt dynamically and continuously to ever changing climatic conditions – and thereby minimize energy requirements. Thermochromic materials are affordable and have a service life of over dozen years. Cost of TLG can be estimated at 50 US$/m2.

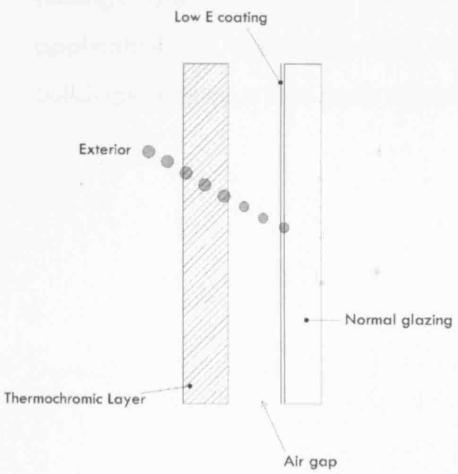

Figure 3. 4: Composition of thermochromic (TC) glazing.

[33] Arutjunjan R.E., et al, *Thermochromic Glazing for 'Zero Net Energy House'*, ZAO METROBOR, Technological University of Plant Polumers, Bor Glass, St.- Petersburg, Russia.
[34] Ibid.

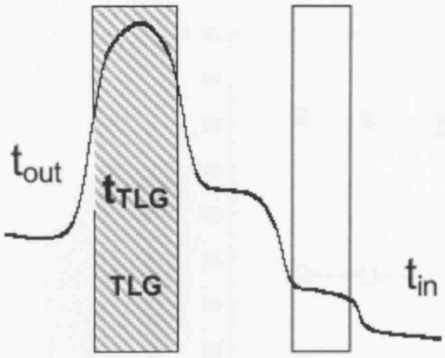

Figure 3. 5: Illustration of heat transmittance, (Source: R.E. Arutjunjan,te al.)

3.2.2 Materials and technology of thermochromic glass

By changing the coordination under influence of light or heat fluxes the newly developed thermochromic laminated glass, which is enforced as previously described with a Low-E coating, can result in a reversible change of transmission and colour of TLG.

The interesting part for architects is the possibility of different aesthetic properties. There are neutral colour conversions from light to dark (grey or brown) but also coloured ones from rosy or yellow to blue and green at the disposal of architects.

Research conducted by Moon-Hee Lee in the Department of Electronic Materials Engineering of South Korea reference[35], showed that when an anti-reflection(AR) coating on a thermochromic glazing VO2 film is used, it can enhance the luminous solar transmittance of the glazing film, while maintaining its thermochromic properties. These findings are particularly interesting, since this AR coating may increase the applicability of thermochromics, and foremost its performance in energy saving of buildings, making it thus more affordable in the construction market (Appendix C).

[35] M.-H. Lee / Solar Energy Materials & Solar Cells 71 (2002)

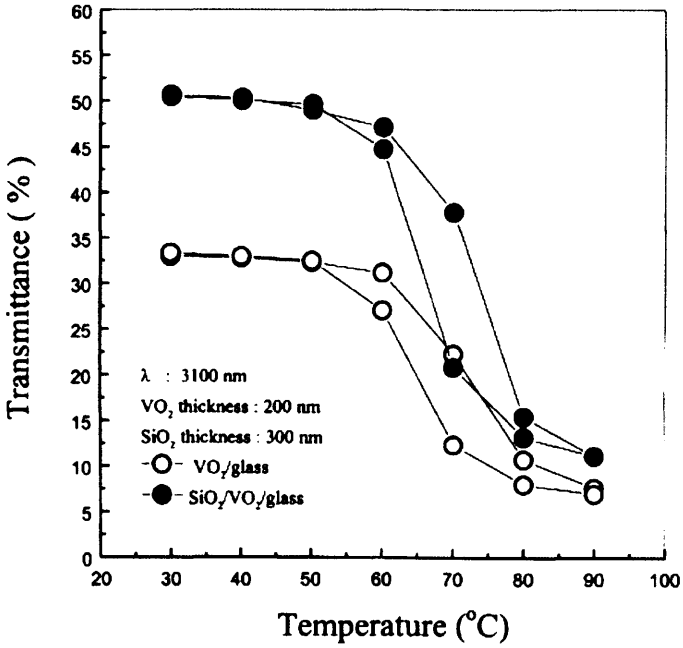

Figure 3. 6: Luminous transmittance ofVO2 thermochromic glazing film with anti-reflection coating showing better transmittance than that without nti-reflection coating.M.-H. Lee / Solar Energy Materials & Solar Cells 71 (2002)

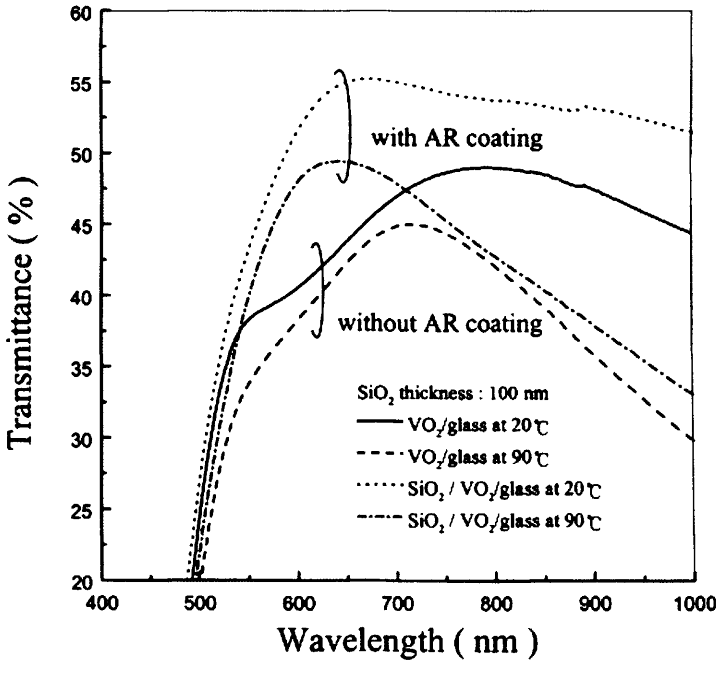

Figure 3. 7: : Thermochromism of VO 2 glazing film with anti-reflection coating showing better thermochromism than that without anti-reflection coating. M.-H. Lee / Solar Energy Materials & Solar Cells 71 (2002)

All of the current research that's being conducted around thermochromism reveals the great potential of this type of glazed technology and the implementation that this may have in the future. The potential of such technology is understandable since the findings are optimistic.

3.3 Solar Shading Devices

Another important element in solar control design process is solar shading devices. These systems can either have exterior or interior control of the incident solar radiation and they can define as drastically the character of the building as glazing. The most common types of shading for the external part of the building are overhangs, fins or full window screen geometries, whereas for the interior louvers or blinds are mostly preferred. The general concept is to intercept direct sun and prevent from overheating during summer season. Operable systems such as blinds provide more flexibility compared to fixed systems and their main advantage is that they can respond directly to the external conditions. Among their benefits is that they increase the occupants sense of comfort, since they can arrange their position and tilt according to their needs. Additionally, louvers and blinds are suitable for every climate. In case of commercial buildings in cold climates, such as UK's, they can be used to control daylight and absorb solar radiation[36].

The main concept of this report is by using careful design of a dynamic façade shading devices can be eliminated; this would allow a clean design and also potentially reduce the long term cost to the owner of the building. No exterior shading makes cleaning of the building easier, no internal shading reduces maintenance costs. Also the possibility of optimum shading might mean the building performs as predicted rather than being affected by the occupants' ability to optimally use internal shading devices.

Based on these findings, this report analyses the possibility of retrofitting the thermochromic glazing on the existing university building of Wates House in order to improve the energy performance and its carbon emissions. The methodology followed in order to achieve this aim is being described in the following section.

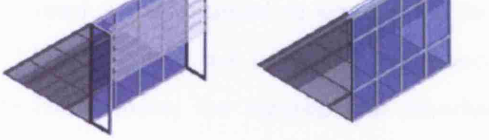

Figure 3. 8: Sketches of various shading devices (Source: Lee Eleanor et al.)

[36] Lee Eleanor, et al., *High-Performance Commercial Building Facades*, Building Technologies Program, University of California, 2002

4.0 Methodology

After evaluating the advanced technologies in glazing elements, thermochromic glass is proposed to be retrofitted in the case study building. It is estimated that by incorporating the 'smart' glazing component the total energy requirements of the building can be reduced, without sacrificing the thermal comfort of the occupants.

This study reviews the current situation of the UCL university building, Wates House, then options for the façade are considered and a design selected. Furthermore, information about building services, elements and conditions are provided and explained in detail for each case respectively.

Further design decisions allow the detailed design of the façade elements; dynamic building thermal analysis software and daylighting analysis software are used to evaluate these decisions.

Results from the thermal analysis are presented. Along with aesthetic considerations these results are considered in the discussion section, leading to the conclusion section where implications of the design are made.

4.1TAS Dynamic building thermal analysis software

At this point it is vital to mention the modelling tools used for the specific research. The most important software was TAS (EDSL[37]), which is a thermal analysis programme. In order to obtain the necessary data to compare the energy performance of both buildings, two models have been created that approached as accurately as possible the existing and the proposed form of the buildings. In the base case model the materials used for the simulations in TAS were taken approximately similar to the ones in the real building. For the new one, on the other hand, materials with lower U-values and better insulating properties were preferred, since the proposed scenario includes apart from the re-cladding, an upgrade of the building fabric in general. A very significant part at this stage was the decision of internal conditions including estimates of the gains from lighting, people and equipment, the infiltration and ventilation rates, as well as the type of heating and cooling used. For the existing building the data used were assumed to correspond to the current conditions, while for the proposed building they are presented optimised according to UK's regulations and suggestions. Furthermore, the appropriate schedules for the internal gains and functions of the HVAC system were applied for each case. The existing building is naturally ventilated;

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[37] http://212.23.11.237/default.htm

therefore the proper aperture schedule was set for both buildings, since the proposed one is using the same strategy in order to provide passive cooling and the adequate air changes in the rooms. A simulation was run thereafter, for both cases and the data obtained involve heating and cooling loads, cost by fuel type and CO_2 emissions which are being collated and compared in the following chapter.

For the proposed building in particular, two more software programs were used. For the purpose of the façade design, 2d and 3d drawings are presented in Autocad. The 3d model created was imported into AGI 32[38] that was used for the lighting calculations. In order to optimise the glazing façade of the building and to assure that adequate surface of thermochromic glazing was used in combination with the other proposed types of glass, a lighting analysis was necessary. The main objective of this analysis was to certify that the minimum necessary daylight factor is being reached within the interior, so that electrical lighting is not used during occupancy hours.

The in depth analysis of the existing case study building and the proposed one, is presented in the following section, showing in detail the assumptions and methods used in each phase of the research.

[38] www.agi32.com

5.0 The re-cladding of Wates House: Case Study building

This section is split into two main sections; the existing building and then the proposed building are described.

5.1 Existing Building

UCL has the majority of its buildings in a small area of Bloomsbury near the centre of London. Wates House is located to the North-East of the UCL campus. It is situated at the junction of Gordon Street and Endsleigh Gardens and as it can be discerned from the map (Figure 5.1) the building has a SE-NW orientation. .

Figure 5. 1: Map of Wates House. Source: Google Map

Among the buildings' construction elements the preponderate material used in the facade is brick, since it is the most representative construction material for the buildings in UK. As can be seen from the following pictures the windows form a pattern grid that is being reproduced for the whole perimeter of the building (floor plan Appendix D).

Figure 5. 2:View of Wates House from Gordons Street Source: Personal library

Figure 5. 3: View of Wates House from Gordons Street Source: Personal library

The structural elements of the building, which is brick faced concrete, are distinct in the façade, dividing its surface in a number of subsections. In these parts two columns of glazing are incorporated that are in turns alternated by transparent and opaque materials. A strong characteristic of its façade' is that it uses its corners in the similar pattern of the glazing columns, which gives a slight feeling of lightness in the overall heavy weight construction.

Firstly an evaluation of the structural components of the building envelope has to take place. Due to the lack of information about the construction of the building, a number of assumptions have been made according to the materials used and their thermal properties. More specifically, the building's main structural element consists of reinforced concrete with external insulation and a brick coating, whereas the internal part is

Figure 5. 4: Detail of the building's east facade Source: Personal library

covered by plaster board. The columns, the beams and the floors are also made from concrete, while suspended ceiling is to be found throughout the floor area that accommodates the ductwork supply and most of the electrical installations.

Approximately 35% of the building is glazed, 20% covered by the dark opaque material and 45% brick. The part of the building that is covered by windows is consisted from single glazing. It therefore allows heat losses and air leakage that aggravates the energy load of the building, while it also allows a great amount of noise from the busy Gordon Street to enter, since most of the windows are open during the day. Additionally, the current situation of the windows, because of the condition and the ageing of their metal framing, is not airtight allowing heat transfer, acting as thermal bridge.

Secondly, at this point it needs to be highlighted that the buildings heating system is consisted of a main boiler that provides heating in each room via wall mounted radiators, which are adjusted to heat till a certain temperature and shut when that is exceeded. The fuel type used for the heating demands of the building is electricity.

The ventilation of the building on the other hand, depends entirely on the occupant control. It is naturally ventilated and considering its construction, it suffers from high temperatures in the interior during the summer months, resulting to its occupants' dissatisfaction.

The building is assumed to have two different principle uses, as a library and as offices. The library is located on the fifth floor of the building, and the rest of the floors are considered to have a common office use. The same assumptions are considered for the proposed building as well, although the internal conditions differ slightly.

5.1.1 TAS Analysis of the existing building

In order to estimate more accurately the energy loads of the existing building, TAS has been used as a modelling tool that can simulate the building's overall performance. The obtained results are going to be compared to the suggested re-cladding of the building's façade, in order to evaluate the necessity of this proposal.

It needs to be emphasized at this stage, that the models created for the TAS simulation (both for the current situation and the proposed one) were divided into a number of zones each one occupying a specific orientation in the building. The applied zoning is summarized in the following figure:

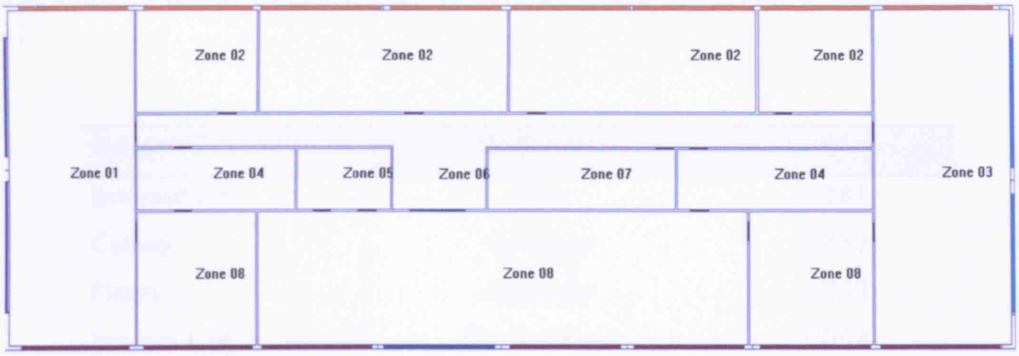

Figure 5. 5: Proposed zoning of hte building that is applied in each zone

Firstly it has been decided that the weather file UK_KEW _76 was applied since the temperatures during the hot season are more representative for the current climate. Table 5.1 gives the average and extreme monthly climate parameters for the standard U.K. reference year as used in the study. All simulations were annual.

External conditions	Month										
	Jan	Feb	Mar	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (°C)											
Average	6.33	5.62	8.82	13.72	19.22	20.57	18.58	14.54	12.06	7.22	3.06
Max	12.4	5.62	17.8	28.4	34.4	43.1	29.3	23.4	19.4	12.7	9.6
Min	-4.2	-1.7	-0.1	4.8	8.4	9.9	7	7.6	3.4	-0.6	-5.4

Table 5. 1 : Weather data, Kew 1976

Furthermore, the building elements assumed for the simulation are summarised in table 5.2, and they are presented along with their estimated U-values.

BUILDING ELEMENT	***Materials***	***U-values***
External wall	Brick	0.381
Ceiling	Concrete	0.753
Floors	Concrete	0.753
Internal wall	Plasterboard	1.054
Glazing	Clear float glass	5.603
Doors/Frame	Steel/Wood	3.844/2.226

Table 5. 2: Building elements according to assumptions and their U-values

5.1.2 Setting the Internal Conditions

Since the case study building is not a recent construction, it is assumed that air leaks through its junctions (especially between the window frame and walls), and therefore the infiltration rate is considered quite high in a value of 1.0 ach compared to a normal one of 0.5 ach. The ventilation of the building in both winter and summer is provided only through the windows since there is no mechanical ventilation system incorporated. In this case a value of zero is used in TAS to show that no air supply is provided my mechanical means.

According to table A2 (Appendix) the recommended density of an occupied space in the centre of the city is 10m^2/person, which is used in this case study. The lighting gain suggested in CIBSE Guide A in the same table, is 8-12W/m^2. For the net floor area of the office area (510m^2) the need for lighting would be estimated at 12 W/m^2.

For the occupancy gains, as well as for the lighting and equipment gains, the calculation has been done according to the figures provided by the Internal Heat Gains chapter of CIBSE Guide A, considering the office floor area and the density of occupation, which was estimated at 10m^2/person. The estimated gains can be seen in the following tables (5.3, 5.4), along with the gains for the library that were calcultated using a similar method.

Office type	Rate of emissions for mixture of males and females		Occupancy gain W/m²	
	Sensible	Latent	Sensible	Latent
For moderate office work	75	55	8	6
Library			6	4

Table 5. 3: Calculation of occupants' gains Source: Humphreys et al (2006), CIBSE Guide A

Use	Density of occupation m²/person	Sensible heat gain W/m²	
		Lighting	Equipment
City centre office	10	12	15
Library	12	10	10

Table 5. 4: Calculation of lighting and equipment gains Source: Humphreys et al (2006), CIBSE Guide A

The operating schedule for the building is assumed as being from 9.00-19.00. The assumptions about building services are described in the following section.

5.1.3 Building services

A lower limit of 21°C and an upper limit of 26°C are assumed for the office zone, and 19°C-26°C for the library area, since the recommended lower temperature for lending is 19°C. The heating and cooling schedule applied in this case is between the hours 8.00-19.00, an hour earlier than the occupancy schedule, since the building needs some time to heat in winter period, or to cool during summer months and reach the comfortable indoor temperatures.

Simulations are run and provide estimates for the number of hours that the temperature of each zone exceeds 28°C and the total heating and cooling loads are calculated and are presented in the results chapter.

5.2 Design criteria of the new façade

The driving motif behind the entire project was a low-energy building as the symbiosis of ecological efficiency and architectural aesthetics – a building that will continue to offer the most up-to-date convenience for operator and user throughout its entire life.
In the life cycle of a building, the initial investment is approximately 30% of the total cost. The remaining 70% are costs that accrue during the rest of the building's operational use. Since a large part of these are energy costs, optimal energy consumption is a key issue in the design process. At the same time, the building needed to offer a comfortable working environment for its occupants as well as provide the flexibility needed to make future changes to office layout with minimal disturbance and cost.[39]

5.2.1 Architectural aspects

Basic consideration in the design of the new façade of Wates House was the creation of an innovative, modern and enthusiastic façade that would pose as a landmark in the UCL's campus. Its architecture should be differentiated from the old version of the building, in terms of aesthetics and materials used. Furthermore, it should provide a different and more intrigue approach than the surrounding environment, in ways that it would escape and surpass the patterns of vernacular architecture, although should keep its beneficial characteristics. The new proposal has to be retrofitted uniformly into the existing site and its modern appearance should keep a rather modest profile in order to comply with UCL's philosophy and trends.
Primary concept was to design a minimal façade that can be both subject to the modern demands of technology and an energy consideration policy without resorting to any radical and extreme changes that would correspond only to an architecture whose main goal was to impress. A very important factor for the design procedure that affected gradually the cladding proposal was the interior space. The proposed façade system needs to provide maximum flexibility in the design of the interior space and a great variety for the exterior. The internal had to be both interesting and spacious, so that it can attract people and most of all provide the necessary conditions for a comfortable indoor environment.

[39] LonMark MAgazine, 'A Symbiosis of Aesthetics and High Tech at Capricorn House in Düsseldorf', p.11, 2006

5.2.2 Energy matters

From an early stage a primary intention was that beside the aesthetic part, the building's façade had to declare a sensitive approach in its design towards energy consumption and CO_2 emissions. Therefore the most appropriate material is considered to be the thermochromic that can meet the new buildings needs and requirements for both aesthetic and energy matters.

The glazing type used should block the long-wave infra-red radiation and therefore reduce the need for cooling in summer. It ought to allow more sunlight to penetrate the building without causing glare problems, while it should have the ability to adjust itself to the incident light without the need of external shading devices that in most cases play a dramatic role in a building's façade. It needs to be appropriate for the climatic conditions of UK and that means that it has to accept more heat gains and restrict losses in winter period, reducing the requirements for space heating, and also block excess heat during summer period. The ability of the occupants to control the ventilation of the rooms was a basic criterion for the design of the new façade, and therefore a strict non openable curtain-wall was rejected from the very beginning.

5.2.3 The Challenge - Design process

According to the previous criteria a façade module was proposed that repeats itself around the perimeter of the building, giving the ability of manual control and natural ventilation.

Firstly the appropriate amount of glazing was considered that needs to be incorporated in the new façade in order to comply with the requirements for lighting, solar gain with the minimum heat losses. The construction of the building needs to be as airtight as possible in order to avoid unwanted air leakage and subsequently losses in energy.

The model created in the case of the new building was more complicated, since a glass envelope had to be designed around the perimeter of the building, which consisted of different types of glazing. More specifically the façade was created by using a recurrent motif. This module was comprised by five different materials; one of them represents a building element (column), whose width remains the same as the base case model, while another part is opaque with extra insulation and a colour finishing on its outer surface (Figure 5.6). The other glazed materials are a semi-transparent part, a transparent and the one representing the thermochromic element. The types of glazed materials of the façade differentiate according to their visible transmittance properties. The most important element of the façade is the thermochromic glazing that, as already mentioned has the ability to change its thermal properties according to its surface temperature. It is this special characteristic of the thermochromic that gives the glazing an interesting appeal aesthetically but in terms of energy as well. The portion of the surface for each glazed material was carefully examined in order to provide a comfortable interior environment. These means that factors such as adequate visible light, which does not cause glare, or sufficient heat gains to minimize costs for heating, had to be confronted by optimizing the module's analogies of its material components (Figure 5.7).

In order to estimate a balanced analogy among the glazed components of the façade module, a calculation of the Daylight Factor (DF) in the interior space was necessary. The calculations took place with the use of the software AGI 32 that estimates the DF achieved in the interior space of the proposed construction and the results were compared to the Building Regulation's recommendations for natural lighting.

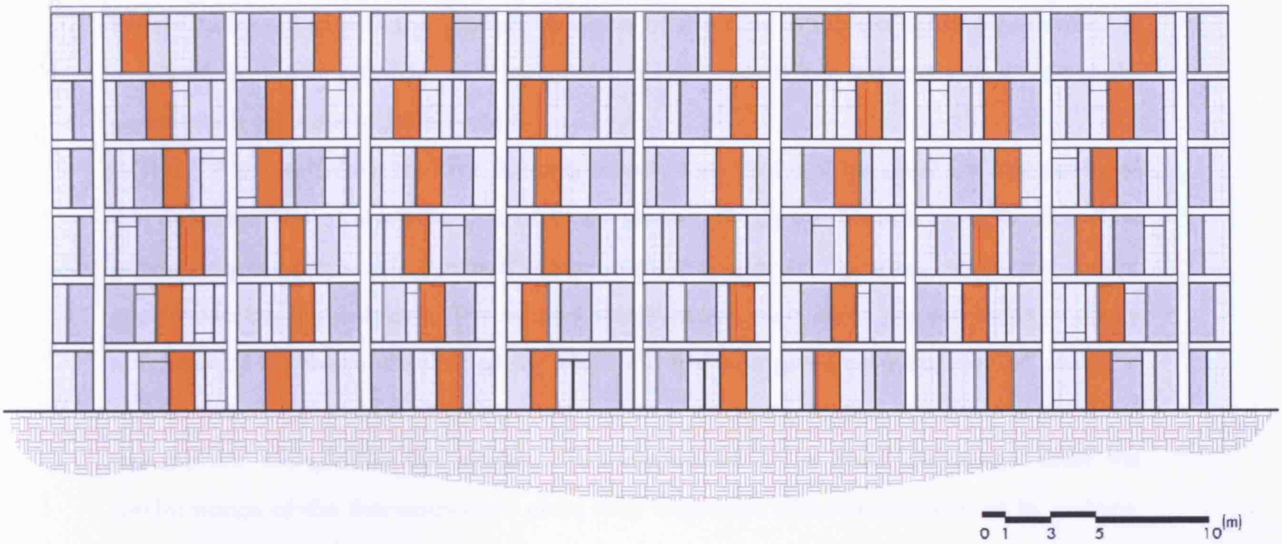

Figure 5. 6: South View of the proposed building

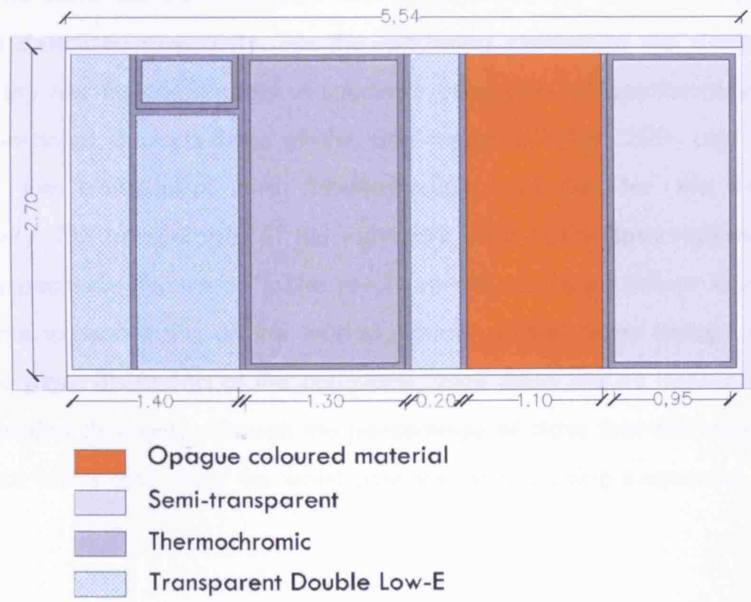

Figure 5. 7: Detail of the proposed facade module with the component elements

6.0 Lighting and thermal analysis of the proposed building

Before proceeding with the thermal analysis of the case studies a lighting estimation is required that will provide with accurate results regarding the amount of daylight penetrating the new façade system.

AGI 32[40] is a software tool for lighting calculations that will be used for the needs of this research. The analysis consists of three stages. Firstly the façade module comprises almost equal parts of thermochromic and transparent glazing, with the latter predominating this analogy. The second stage proposes a clear predominant analogy in favour of the thermochromic glass, while the last one gives an indication of what the results would be in both lighting and thermal analysis, in the extreme case of no transparent material in the module. This appealed as a good challenge since the performance of the thermochromic glass may improves with the increase of its surface, although the results concerning daylight factor are ambiguous. Therefore in the following an analysis is carried out for each of the cases that are of interest.

6.1 Daylight analysis

First step for the daylight calculation procedure was to create a 3D model in AutoCAD that resembles a typical floor of the proposed building. The model was then imported in AGI and materials were applied that reciprocate the visible characteristics of the materials described previously. For the rendering procedure the data used were an overcast sky and the coordinates of London's geographical location (Appendix E).

The proportional characteristics of the first stage included 29% and approximately 23% of the transparent and thermochromic material for the façade module respectively. The percentages of the materials used in this case represent 1.60m and 1.30m respectively (Figure 5.7). The results of the rendered image show that DF over exceed the expected 5% on the working plane of the rooms (Image 6.1). This could result in a glare discomfort of the occupants, since there are no internal control systems that can adjust daylight, although the percentage of days that this may occur is rather small, since in this case study the worst case scenario is being examined.

[40] www.agi32.com

9.81	7.36	7.71	6.52	7.32	6.34	7.22	6.29	7.18	6.28	7.24	6.34	7.39	6.56	7.80	7.61	11.75
8.00	5.13	4.38	4.03	3.88	3.80	3.76	3.73	3.73	3.73	3.77	3.80	3.92	4.08	4.48	5.33	8.32
7.56	4.65	3.81	3.44	3.27	3.19	3.14	3.12	3.11	3.12	3.15	3.20	3.30	3.49	3.90	4.80	7.74
7.94	5.07	4.32	3.98	3.83	3.74	3.70	3.68	3.67	3.67	3.71	3.75	3.86	4.02	4.42	5.28	8.26
9.88	7.23	7.51	6.40	7.11	6.21	7.00	6.16	6.96	6.16	7.04	6.22	7.16	6.43	7.60	7.49	11.75

Figure 6. 1: Daylight Factors obtained for the first case module components, with an analogy of the transparent and thermochromic glass 29% and 23% respectively.

For the next case the model designed incorporated only 16% of the transparent material, whereas the thermochromic is applied to a 36% of the total surface of the module. The results regarding the daylight factors can be viewed in the following image.

6.07	3.60	4.19	3.13	4.04	3.08	4.03	3.10	4.02	3.11	4.07	3.18	4.18	3.37	4.53	4.26	8.73
4.58	2.07	1.77	1.65	1.64	1.61	1.63	1.61	1.64	1.64	1.68	1.71	1.81	1.97	2.34	3.17	6.37
3.33	1.98	1.74	1.67	1.64	1.63	1.63	1.63	1.64	1.65	1.68	1.74	1.84	2.03	2.44	3.33	5.84
4.96	2.69	2.49	2.44	2.42	2.41	2.40	2.41	2.41	2.43	2.46	2.51	2.62	2.80	3.21	4.11	7.15
7.08	5.21	5.50	5.00	5.43	4.96	5.41	4.95	5.40	4.96	5.49	5.03	5.62	5.27	6.08	6.40	9.89

Figure 6. 2: Daylight Factors obtained for the second case module components, with an analogy of the transparent and thermochromic glass 16% and 36% respectively

7.00	4.69	4.83	4.06	4.56	3.92	4.50	3.90	4.46	3.90	4.49	3.93	4.58	4.04	4.83	4.66	7.13
5.20	3.20	2.70	2.46	2.36	2.30	2.28	2.26	2.26	2.26	2.27	2.30	2.35	2.45	2.67	3.17	5.17
4.64	2.86	2.33	2.10	1.99	1.93	1.90	1.89	1.88	1.88	1.90	1.92	1.98	2.08	2.31	2.83	4.60
5.04	3.10	2.65	2.44	2.32	2.26	2.23	2.21	2.21	2.21	2.22	2.25	2.30	2.39	2.60	3.06	5.01
6.41	4.47	4.87	4.05	4.42	3.82	4.33	3.79	4.30	3.79	4.34	3.82	4.41	3.92	4.63	4.42	6.55

Figure 6. 3: Daylight Factors obtained for the third case module components, with the transparent part being all substituted by thermochromic glass

Finally, the case at which only thermochromic material is used can be seen in figure 6.6 where it is obvious that the luminance in the interior space is reduced significantly.

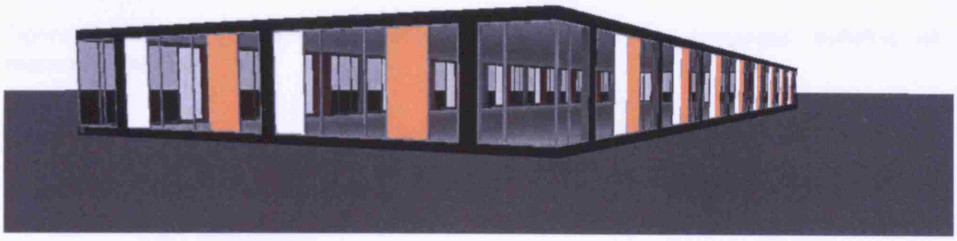

Figure 6. 4: Exterior view of the proposed building of the all glass case

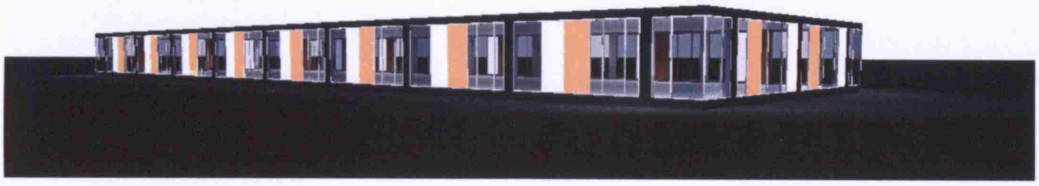

Figure 6. 5: Exterior view of the south facade of the proposed building of the1.30_1.60 case

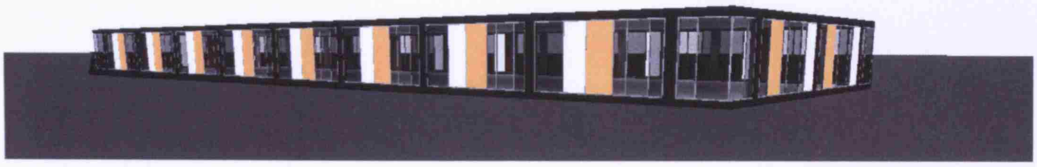

Figure 6. 6: Exterior view of the south facade of the proposed building of the2_90 case

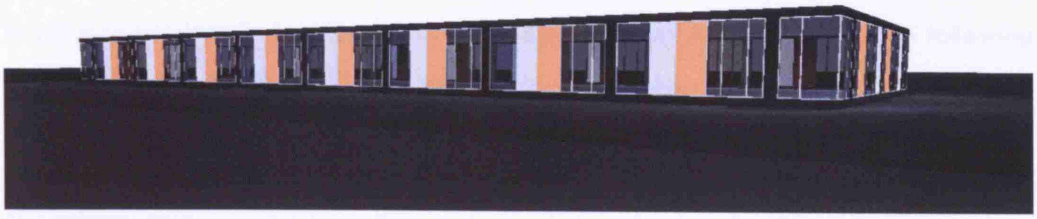

Figure 6. 7: Exterior view of the south facade of the proposed building of the all thermochromic case

6.2 TAS Simulation of the proposed building

In order to simulate its function as realistic as possible in TAS programme, the following technique was applied.

Since the appropriate analogies of the glazing materials have been made clear, a model was created in TAS that approached the proposed design as much as possible. The zoning of the model is similar to the one described in the first part of the base case. Moreover, while arranging the parameters, the same weather file and schedules were set in order to compare the results between the two buildings with more ease and accuracy.

Furthermore, the appropriate selection of materials took place that can be seen in table 6.1. The new materials have to comply with the Building's Regulations Part L for refurbishment and therefore their U-value has to be lower than the limitations presented in Chapter 2.

Building Element	*Materials*	*U-values*	*Standard for replacement thermal elements*
External wall	insulated concrete cavity wall	0.28	0.35
Ceiling	Concrete	0.2	0.20
Floors	Concrete	0.25	0.25
Internal wall	Plasterboard	1.05	
Opaque material	insulated plaster finish	1.05	
Doors/Frames	wood/aluminium	2.22/4.25	

Glazing type	*Materials*	*U-values*	*Limiting U-value*
Transparent	douple pane/Low-E coating	1.36	3.3
Semi-transparent	douple glass with a diffuse outer pane	1.8	3.3
Thermochromic	triple pane/Low-E coating with internal blind	0.89	3.3

Table 6. 1: Proposed materials for the new building and their U-values

The most challenging part of the simulation in TAS was to set the appropriate parameters for the correct function and material of the thermochromic glazing. Due to the double nature of the glazing, transparent while at its cold state (below a certain temperature) and darker at its warm state, there had to be created two types of materials that would approach both states. The basic material used to represent the spectral characteristics of its clear state was a double-pane glass with low-E coating and a low U-value. The material used to represent its dark state was more complicated (Table 6.1). Since in the programme such advanced glazing types are not yet incorporated, a glass with similar characteristics and performance of thermochromic glass had to be created. Therefore a glass with multiple layers (triple pane), low-E coating and blinds was created, with the external glazing slightly tinted, having anti-sun properties (figure 6.8). According to a research presented in previous chapter, it was proved that despite some doubts thermochromic glazing could retain its visible transmittance to a satisfactory level[41]. Therefore the proposed dark state in TAS glass had a similar (relatively high) visible transmittance value (0.30) in order to minimize the need for electrical lighting, while its solar transmittance was kept at low levels (0.10) in order to block the far-infrared radiation.

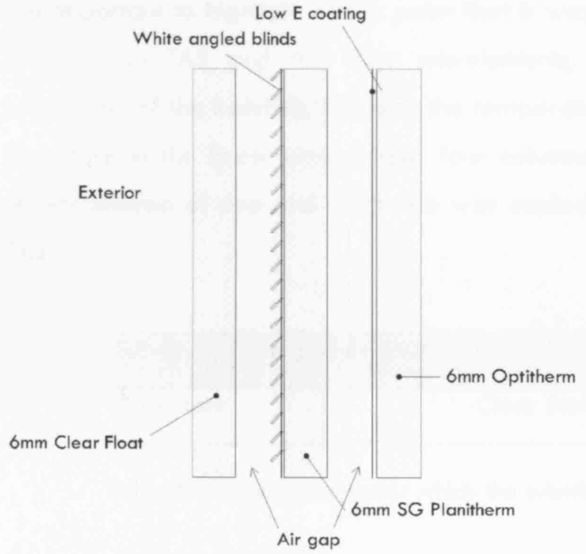

Figure 6. 8: Detail of the assumed elements of the thermochromic glass for the needs of TAS simulations

After applying the materials to all building components a substitution schedule had to be created that would instruct the programme to follow a certain function. The first material, the transparent, is the default and the second, the thermochromic one, replaces the first when certain conditions are met. These conditions are relative to the temperature at which the thermochromic glass changes its characteristics. This switching temperature was set at 19°C (table 6.2) which means that when the external surface

[41] Lee Moon-Hee and Jun-Seok Cho, 'Better thermochromic glazing of windows with anti-reflection coating', Department of Electronic Materials Engineering, The University of Suwon, 1999

of the thermochromic pane would reach this temperature it would automatically change into its dark state. In order to find out which hours the glass exceeds this limit, a simulation was run for the whole year with the glazing being at its 'cold' state. The temperatures obtained for the outer surface of the glass for the whole year were introduced in an Excel spreadsheet output file. In this file a column was created with the surface temperatures of the thermochromic glass for every hour throughout the year. Thereafter a custom made command was created in Excel that interprets the temperatures below 19°C as zero (0) values, representing the 'cold' state, while the rest as one (1), which is the 'warm' state[42]. This schedule was copied in the substitution schedule of TAS, which was then asked to replace the thermochromic glass in the 'cold' state with the thermochromic glass in the 'warm' according to the schedule and one more simulation was run. When the schedule is at the value of one, above the switching temperature, the 'warm' state of the glass is used that reflects more and transmits less in the Infrared part of the spectrum. By using this function in excel it was managed to switch the states of the thermochromic glass according to its temperature.

It is important to highlight at this point that it was necessary to create four substitution schedules in TAS and thus four sub-elements, each one representing a different orientation of the building, because the temperatures would be different on each side. Therefore in the Excel spreadsheet four columns with temperatures were created in reality instead of one and each one was copied in separate substitution schedules in TAS.

Substitution temperature for thermochromic glass is:			**19 degrees**
Dark state	1	Clear State	0

Table 6. 2: Conditions under which the substitution function was created

Percentage of hours that the external surface of the thermochromic exceeds the limit of 19°C				
	North	East	South	West
% dark time	16.10	17.90	17.36	16.63

Table 6. 3: Percentage of hours that the external surface of the thermochromic

42 The function in Excel was created by Dr. Ben Croxford – Lecturer, The Bartlett School of Graduate Studies.

From the last simulation, data were obtained from the temperatures of the same glass panes used for the creation of the substitution schedule and they are compared to the previous ones. Simultaneously, total loads were collected for heating and cooling of the new building and they are being compared in the following chapter to the total loads of the base case model. The main purpose of this section then, is to evaluate whether the use of the thermochromic glass will provide savings in the total loads of the building in the case of a refurbishment of the existing. During the analysis double glazing is being used as well and therefore it is vital at this point to present the impact that this type of glass has on the building compared to the existing case and to the proposed thermochromic type.

7.0 Results

In this chapter there will be a discussion about the results obtained and correlated from the previous stages of this report. The results obtained from the existing building which is considered as the base case are going to be compared to the rest of the data collated from the other case studies.

7.1 Overheating hours

According to Cibse Guide A buildings that are naturally ventilated have a benchmark overheating criteria of 28°C not being exceeded for 1% of the annual occupancy hours (Appendix F). In the following tables the number of hours of this limit is presented for the base case model, the proposed building when double glazing is used and the second version of it with the thermochromic glass, assuming that in all cases no air-conditioning is applied. The results used are taken from the 3rd and 5th floors of the three types of building, representing a typical and the library floor area respectively. According to the following chart the performance of the base case in summer is much worst compared to the double glazing and to the case of the thermochromic.

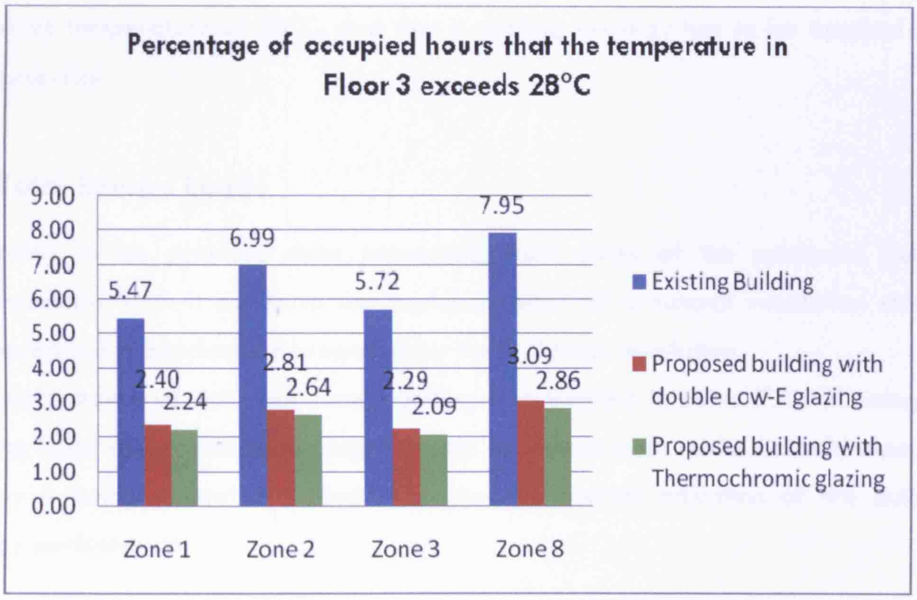

Chart 7. 1: Number of hours that the temperature in Floor 3 (typical Floor) exceeds 28°C, during occupancy hours

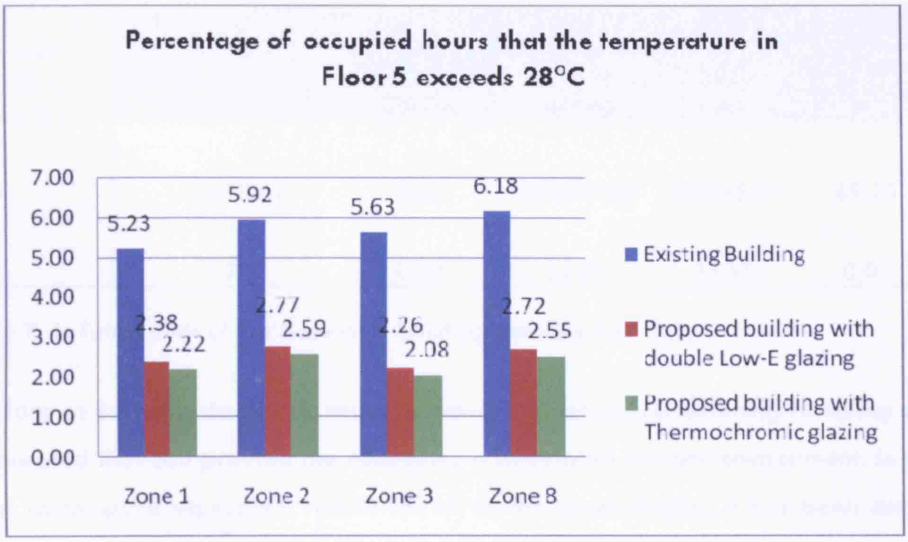

Chart 7. 2: Number of hours that the temperature in Floor 5 (Library) exceeds 28°C, during occupancy hours

This is probably due to the fact that the construction materials of the proposed building are more efficient, since they have lower U-values and mostly due to the performance characteristics either of double glass with Low-E or the thermochromic glazing. The percentage of overheating of the thermochromic (approximately 2.5% for both zones) in this case is relatively good, giving similar results to the double glazed case (2.7%). It has to be pointed out though that these figures exceed the 1% annual hours of operative temperature of 28°C, and thus a cooling strategy has to be applied in the new proposal.

7.2 Total Energy Loads

According to the previous data presented, both cases of the proposed building underperform when it comes to the implementation of a natural ventilation strategy compared to the benchmarks proposed by the buildings regulation.

The performance of the base case building is presented in table 7.1. Heating and lighting loads are evaluated during a yearly and daily basis while the total amount of energy is being estimated in order to give an overall indication of the buildings energy performance.

Base case Building	Loads (kWh)				
	Heating	Cooling	Lighting	Total	m²
Year	102668.79	0.00	200876.53	303545.31	69.23
Day	11.72	0.00	22.93	34.65	0.01

Table 7. 1: Total Loads of the base case building annually and daily

Therefore at the next stage it is recommended that an air-conditioning handling unit is incorporated that can provide the necessary comfortable in-door environment. In order though to compare equivalent results for all of the cases studies, it has been assumed at this point that the base case building has a cooling system with the same schedules and temperatures as the new proposal.

Case Studies	Annual Loads (kWh)				Total improvement on the base case
	Heating	Cooling	Lighting	Total	
Base case (1st Building)	98843.65	75324.99	200876.53	375045.17	0.00
1-Double glazing Low -E	25821.03	73427.88	190713.77	289962.68	85082.49
2-Thermochromic glass 30_60	17564.69	68730.18	164830.40	251125.27	123919.90

Table 7. 2: Total annual Loads for each case, assuming cooling is applied to the base case building

From the following chart it is easy to comprehend that the loads for heating in the base case are much higher than the other case studies and this is due to its fabric and its construction (high rate of air infiltration). In the other two cases the heat gains from the extended glazing reduce significantly the needs for heating, but on the contrary the cooling load is slightly decreased during summer period. The thermochromic is giving a better result but still it does not perform as expected. When it comes to lighting requirements, both façade types, double glazing and thermochromic, behave similarly reducing the load compared to the base case. Such a result was after all expected since the glass façade proposed allows more natural light to penetrate, reducing thus the need for electrical lighting. It has to be mentioned though that for the case of the library a special schedule has been created according to which lights were on during the occupancy hours and especially for the reading section, since the requirements there are higher than the rest. Finally, when observing the total loads of the three cases it can be easily seen that the most energy consuming case is the existing building, something that was already expected, while the most energy saving is the one with the case of the thermochromic.

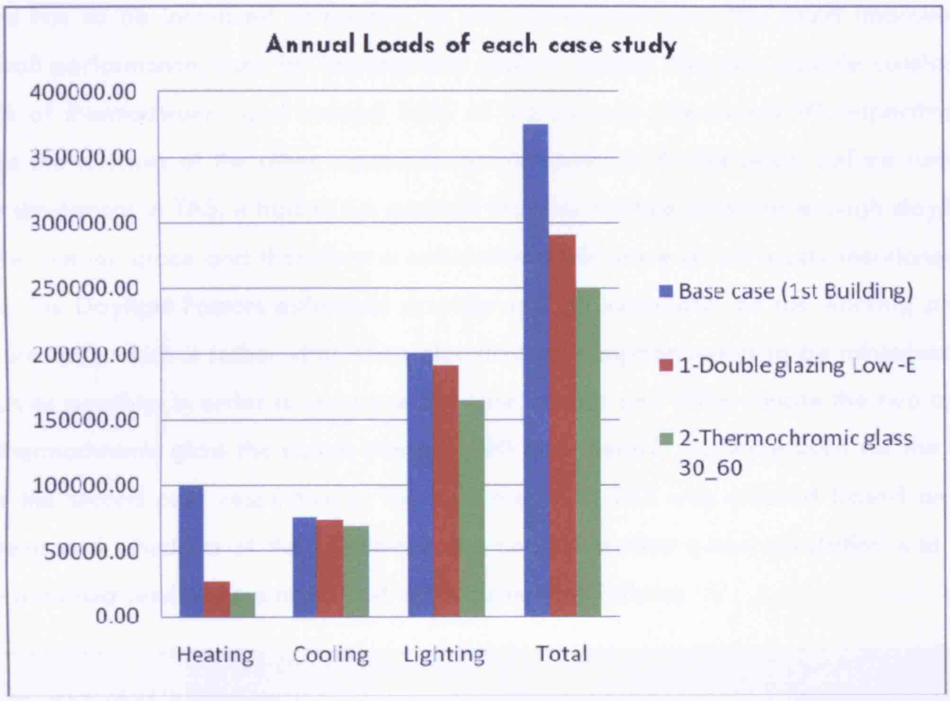

Chart 7. 3: Annual Loads of each case study

The performance characteristics of the thermochromic glazing can provide adequate solar resistance during the summer period, and reduce the cooling needs. Nevertheless it is observed that in winter time its performance is quite satisfactory, but not better than that of the double glazing since its switching temperature is set at 19°C and such temperature is not feasible during that period.

Although the results are relatively positive, thermochromic might be expected to correspond to greater energy savings and thus reduced total loads. One logical explanation for non expected results may be that the current area of the thermochromic glass used is not adequate for it to function properly as estimated in the beginning of this report. In order to improve its efficiency and performance a re-arrangement of the facades components had to be considered.

7.3 Case study with re-designed facade

The module used in the previous comparison comprised, as already mentioned, 1.30 m of thermochromic and 1.60m of transparent double glazing with Low-E coating (23% and 29% respectively), didn't give the expected results. Therefore a new analogy of the façade's module had to be proposed. In the new case study the thermochromic glass has to be increased compared to the transparent one; this could improve its overall performance, both for heating and cooling season. The new module consists of 36% of thermochromic and around 16% of transparent (2m and 0.90 respectively), while the surfaces of the other materials remain constant. At this point, before running any simulations in TAS, it had to be assured that this module provides enough daylight in the interior space and therefore a calculation took place as all ready mentioned in AGI. The Daylight Factors estimated provide enough luminance on the working plane (figure 6.2), which is rather vital when electrical consumption needs to be minimized as much as possible. In order to compare the case studies and differentiate the two cases of thermochromic glass the names therm30_90 and therm2_.90 were used for the first and the second case respectively. The new model in TAS was created based on the systems and schedules of the previous cases and thereafter a new simulation was run. The obtained results are summarised in the table that follows.

Case Studies	Annual Loads (kWh)				Total improvement on the base case
	Heating	Cooling	Lighting	Total	
Base case (1st Building)	98843.65	75324.99	200876.53	375045.17	0.00
1-Double glazing Low -E	25821.03	73427.88	190713.77	289962.68	85082.49
2-Thermochromic glass 30_60	17564.69	68730.18	164830.40	251125.27	123919.90
3-Thermochromic glass 2_0.90	17618.20	65235.64	164830.43	247684.27	127360.90

Table 7. 3: Total annual Loads for each case, including the new case of Thermochromic glass 2_0.9

In this case as well it is easy to comprehend that heating loads remain the same even in this case scenario. The reason is simple; during the winter time the number of hours that the glazing overcomes the switching temperature of 19°C is zero. Therefore the glass remains at its "cold" state which is represented by the double glazing with Low-e coating and thus it has the same requirements with case study 2.

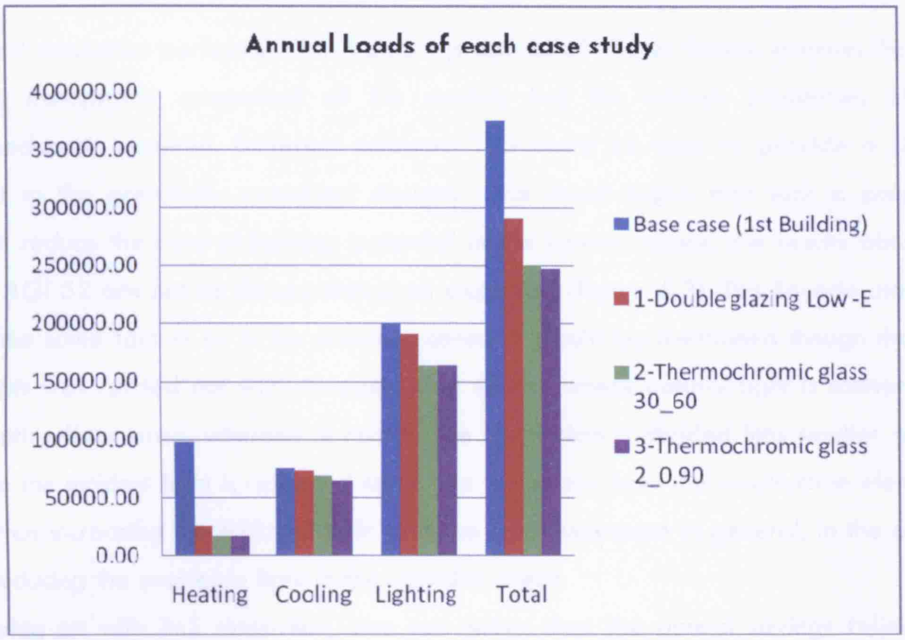

Chart 7. 4: Annual Loads for each case study

On the other hand the cooling demands were decreased compared to the previous case, showing in that way that the hypothesis made about the analogy between its surface and its performance may prove correct.

It might be interesting at this stage, to point out that the performance of the thermochromic glass may improve during the winter months only if the switching temperature drops lower than 19°C. This will increase the number of hours of its performance, which will result in extra savings in heating loads. Although such an approach would be very interesting, this report has only investigated variables in the surface that they require in order to perform at its best, and considers this "limit" temperature fixed.

7.4 Full thermochromic façade

The last simulation performed for the new proposal of Wates House, assumes that the whole transparent component of the module has the intrinsic properties of the thermochromic material. Different coloured TLG could be used to provide a similar effect to the previously proposed designs. One could argue that such a proposal would reduce the natural lighting potential in the interior space, the results obtained from AGI 32 are not as disappointing as expected (figure 6.3). This façade may not give the same factors as in the previous cases; it should be mentioned though that the analysis was carried out with an open plan model, where natural light is scattered in the entire floor area, whereas in reality the floor plan is divided into smaller rooms, where the incident light is reflected back into the space from the construction elements, and thus increasing the diffused light and the total luminance in general, in the offices but reducing the available light in the corridor areas.

Carrying on with TAS simulation, one can notice that the annual savings follow the same guidelines described previously. Lighting loads, as can be seen from chart 7.5, remain constant for the 2nd and 3rd case, but in the last one they are slightly raised; this means that the demands for supplementary electrical lighting are greater, something that was already ascertained by the simulation in AGI. Due to the reduced visible transmittance of the outer pane of the thermochromic it does not allow the same quantity of light and therefore the hours that the electrical lights are on are increased compared to the previous cases. Therefore, although it decreases substantially the cooling demands, the overall performance diminished due to its intrinsic properties.

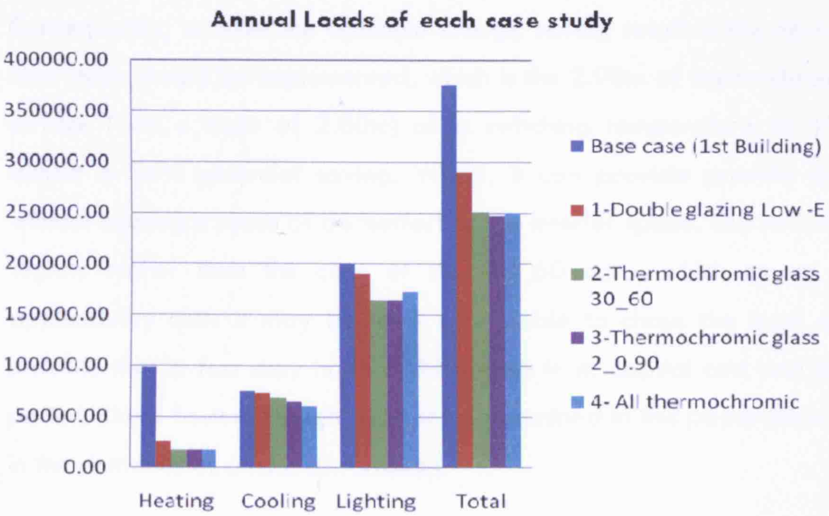

Chart 7. 5: Annual Loads for each case study

Chart 7.6 shows in percentage terms the energy reduction potential for the different areas of thermochromic glazing. It clearly demonstrates that a balance has to be kept; when increasing its surface the heating and cooling savings ameliorate but there is a limit to the surface it ought to occupy since after that limit it underperforms regarding lighting demands. Another comment is that although the implementation has proved more cost effective compared to the double Low-E glass (33% and 22.% savings respectively), when tested on different surface analogies the difference was only at 1%.

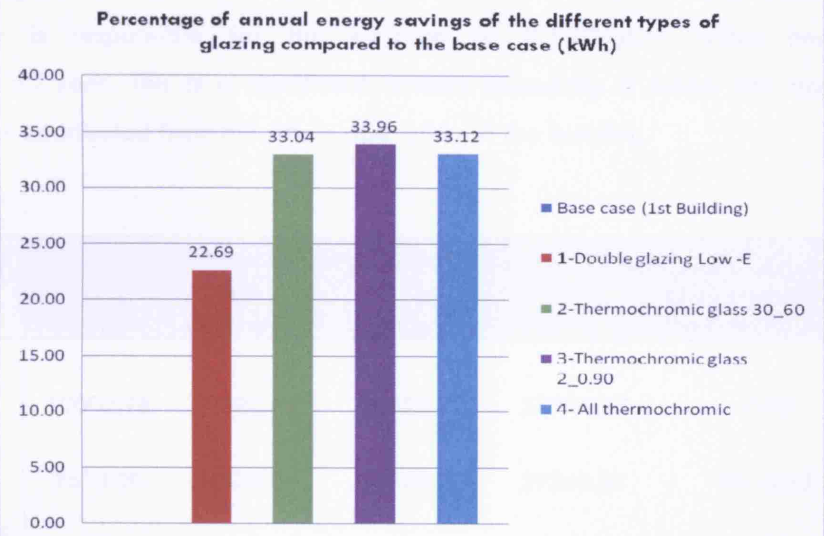

Chart 7. 6: Percentage of the annual energy savings estimated for each one of the types of glazing, compared to the base case building.

Consequently, to have the optimum energy saving result in the new building the third case study should be implemented, which is the 2.90m of thermochromic or else 8.12m^2 surface (with a hight of 2.80m) of a switching temperature at 19^{o}C, that reaches almost a 34% potential saving. Whilst, it can provide provide adequate daylight wihtout causing a sense of discomfort to the interior space. This reduction though is only slightly higher than the case of the 30_60 case, which means that in terms of applicability costs it may be most affordable to chose the least amount of surface possible that in fact may have a difference in its capital cost and thus in its payback period. These factors though will not be examined in this paper since such a research is in the demands of a new dissertation.

The current building's HVAC system is operated via the electricity grid, thus the assumption was made that the proposed one will have the same operational systems in order to make compatible comparisons between the case studies. In case of using the proportion suggested earlier, we get a reduction of 127,360.90 kWh of the total energy consumption. Since the heating and cooling demands are assumed for all the under-study cases to derive from electricity, normalized over the 4814.67m2 of the building's total floor area, the energy consumption amounts for 26.45 kWh/m^2/year. Taking into consideration that the cost of electricity is 10.12p/kWh[43], the estimated cost saving for the selected case study is 2.68£/ m^2. Furthermore, each kWh of electricity is responsible for the emission of 0.127kgC[44], which amounts to 4.33kgC/m2·year. This is a significant amount especially if taken into account the reductions contributed from the whole operation of the building.

Case	Annual Energy Costs (£)				Total omprovement on the base case	% Energy saving
	Heating	**Cooling**	**Lighting**	**Total**		
Base case (1st Building)	10002.98	7622.89	20328.70	37954.57	0.00	0.00
1-Double glazing Low -E	2613.09	7430.90	19300.23	29344.22	8610.35	22.69
2-Thermochromic glass 30_60	1777.55	6955.49	16680.84	25413.88	12540.69	33.04
3-Thermochromic glass 2_0.90	1782.96	6601.85	16680.84	25065.65	12888.92	33.96
4- All thermochromic	1778.58	6141.43	17463.59	25383.60	12570.97	33.12

Table 7. 4: Annual Energy Costs for all the under study cases, and their savings potentials compares to the existing building

43 http://www.dti.gov.uk/energy/statistics/publications/prices/tables/page18125.html
44 The Government's Energy Efficiency Best Practice Programme, December 2000. *ECON 19*, p.22

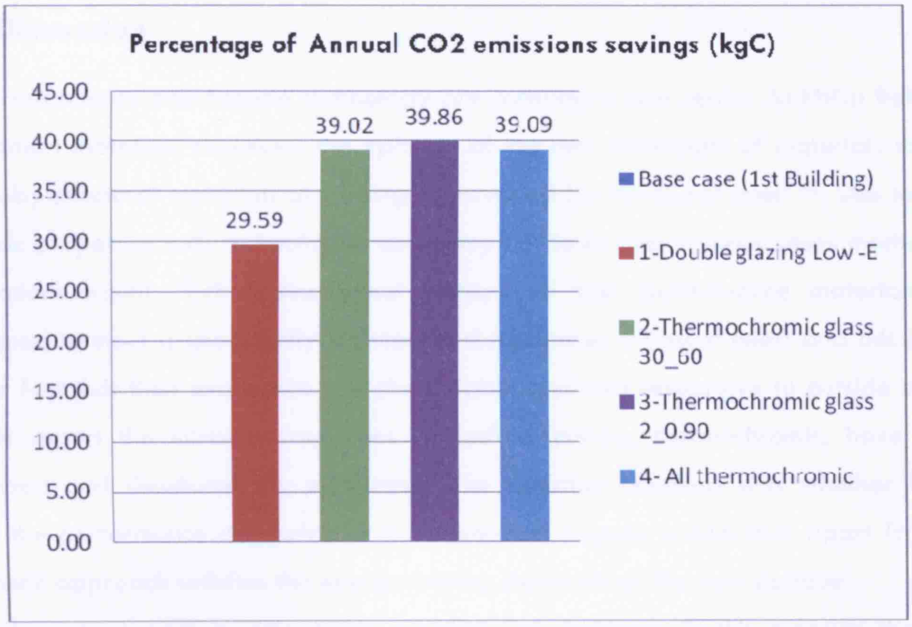

Chart 7. 7: Annual CO_2 emissions savings (kg C/kWh)

8.0 Discussion

Materials science and façade technology are entering a new realm. As Philip Ball puts it: " Smart materials represent the epitome of the new paradigm of materials science whereby structural materials are being superseded by functional ones"[45]. Due to their intrinsic properties such technologies can carry out tasks that in some cases mechanical operations would. Such technological systems of high performance materials are designed to meet a specifically defined and sometimes transient need and this is due to the fact that their properties are changeable and thus responsive to outside stimuli. In this report the intrinsic properties of such a system, thermochromic, have been discussed and simultaneously evaluated. The question assessed was whether it can meet the performance standards of a 'responsive' façade system that apart from an aesthetic approach satisfies the energy-saving demands of the new époque.

Façade systems pose an intractable problem for designers. In this occasion the case study UCL departmental building of Wates house was used to test an innovative proposal. A challenge was set to re-clad the building with a modern and aesthetically appealing façade that has to be interesting, conveying a modern dynamic image, and be energy efficient, according to the current environmental policies. In order to meet this challenge, a glazed façade module was proposed that enwraps the building, whose module consists of 3 different kinds of glazing. One of those is the thermochromic glass. The choice of this particular type of glass is based upon the initial intention to make the building as interesting as possible, by means of combining different kinds of glass and mixing opaque with transparent elements. It also had to provide lighting control according to the needs of the offices and the library that the building hosts. The purpose of the study then was to evaluate the dynamics of the thermochromic façade, since its characteristics seem very promising. Therefore one of the most important intentions was to create a dynamic façade that would not incorporate shading devices or canopies, nor would it implement photovoltaics, since their research and analysis have been conducted several times in the past.

Thermochromic seems to offer plenty of opportunities in building design. It is extremely pleasing for architects and provides great chances for varieties and combinations in façade construction. They also provide a great chance for not having shading devices, although shading may be an efficient way of reducing solar gains when used perfectly by the occupants. In practice though, tenants never behave as expected. Occupants

[45] Smith Peter F., Architecture in a Climate of Change, A guide to sustainable design, Architectural Press 2005, p.260

can have a sense of comfort when it comes to light control especially during summer period. In theory the most simple and basic component for comfort is internal blinds that are incorporated in a building's façade. People tend to feel better when having control over the operation of blinds or other shading devices, since they can change at any time the internal conditions according to their needs and requirements. In practise though, the situation differs due to the multiple needs of the people present in the same environment, as in the case of public buildings. Field studies show that they rarely adjust the angle of the blinds according to the sun's position and therefore resulting to their dissatisfaction and to an extended feeling of discomfort (Rubin and Collins, 1978). The study also shows that after having adjusted the blinds they will not re-arrange it for the rest of the day. Nevertheless the presence of a number of people in one space means different needs and thus different sense of comfort; in particular in a building such as Wates House whose facades are all exposed to daylight and the manual operation and control of the blinds is not always feasible. Lighting control systems such as blinds may fail repeatedly their purpose due to the lack of occupants' response and initiatives and sometimes during the hot period the may overheat increasing the cooling demands in the interior space. It has to be pointed out as well that blinds can be also non beneficial due to their cost for implementation on the whole façade. If such system is dynamic then it can be even more expensive and if it is mechanical then it may break in a short period of time and their replacement may add extra expenses to the maintenance and operation of the building.

On the other hand, thermochromic systems can provide great advantages in daylight adjustments without the occupants' interference, since they are passive control mechanisms. Their transmittance and colour are dependent on the temperature of the outer glass pane. According to the radiation of the incident light on the building's façade, they can change their colour and their visible transmittance thus adapting to the external climatic conditions. In that way they filter the external stimuli, leaving the interior environment in the appropriate comfort conditions. Furthermore, the adapting procedure of the façade and thus the change of colours create an interesting and stimulating indoor space that attracts and activates its occupants.

The results obtained from this report were satisfactory compared to the present condition of the building. The basic criteria of this research was to find out the appropriate surface that this material ought to take up, in order to perform at its best for the specific building. Simulations and daylight analysis of the building showed during the process that the more surface it occupies the better it performs although there is a limit to its extend since we have to consider the restrictions coming from the daylight requirements. It has to be sufficiently daylit in order not to allow any wasteful energy consumption from electrical lighting.

The simulation process carried out follows a logical process in terms of thermal and lighting analysis of the building. The results obtained may show a positive trend but the percentages of the annual savings may not cover the capital costs of the total building's façade. As a new technology, thermochromic glazing is more expensive than an ordinary glass type ($50\$/m^2$)[46]. Its cost analysis hasn't been carried out in this paper, since this could probably be a completely different subject for dissertation. When compared though to the other types of advanced glazing, thermochromic seems to be the cheapest especially compared to the electrochromic glazing. Thermochromic might be more expensive compared to double or triple glazing, but offer several benefits in terms of mitigations of energy demands and loads as well as architectural design opportunities.

However, low luminous transmittance (usually 30–40%) of the thermochromic glazing film and the difficulty of fabricating a large area coating are two major obstacles in commercial production of this thermochromic glazing films. Although large area coating techniques have been developed recently, the problem of low luminous transmittance of this glazing film has not yet been solved. However, there seem to be ways to increase the luminous transmittance of the thermochromic glazing film as explained earlier on this paper. Such techniques may increase slightly the cost of its fabrication but its energy savings on the long term can compensate for its present worth.

[46] Arutjunjan R.E., et al, *Thermochromic Glazing for 'Zero Net Energy House'*, ZAO METROBOR, Technological University of Plant Polumers, Bor Glass, St.- Petersburg, Russia.

9.0 Conclusion

It is a current belief that the energy load associated with conditioned internal environments can be avoided with the assistance of intelligent control systems. This means that the zero energy building (zero operational energy) is an achievable goal, using only renewable resources and incidental heat gains to 'drive' a building's comfort system[47]. In this report thermochromic glazing has been researched, that is part of such a technological system and it is considered a significant contributor towards minimising the use of energy in buildings.

A module is being proposed that creates a recurrent motif around the building structure. This type of module contains the thermochromic glass and its performance compared to the existing building was investigated. The proposed building was firstly examined without cooling in order to compare its performance to the existing one, and as expected it under performed, reaching up to 2.9% of overheating in the worst case, especially in the summer period due to its extended glass façade.

The thermochromic glass was considered to maintain a stable switching temperature of 19°C and all the case studies were evaluated according to this criterion. Four different cases were examined; in the first one it was assumed that the thermochromic didn't switch states and remained constant with its double pane Low-E properties; this case was examined in order to estimate whether double glass would suffice for the needs of the under study building. The results showed that thermochromic glass compared to this efficient type of glazing, it improves at a rate of almost 10% the buildings' total energy savings.

The second case of the façade module consisted of 23% of thermochromic against a 26% of the double glazing, while in the third case the majority of the module's surface occupied the thermochromic glass, with an analogy of almost 2:1(2m and 0.90m respectively). Finally the last simulation took place considering that thermochromic occupied the whole surface of the transparent glazing and examined its potential improvements.

AGI and TAS simulations showed that the best performance of all the thermochromic cases had the 2_90case.

For all of the cases a lighting study was undertaken, considering the thermochromic at its dark state, when the visible transmittance is at its lowest, so as to assess the quality and factor of daylight that such glazing would have in the interior space. The most

[47] http://www.tech.plym.ac.uk/soa/arch/intel1.htm

appropriate type according to the estimations is the type of thermochromic 2_90, which gives the most satisfying daylight factors.

When running TAS simulations on the other hand, results showed that the optimum performance with the most savings in energy consumption was the all-thermochromic state. Although this seems to be the most efficient it deteriorates the natural lighting levels in the internal space. These three cases, the 30_60, 2_90 and all-thermochromic don't have a great difference on their annual energy savings (33%, 34% and 33% respectively), therefore the most appropriate one for the under study case was evaluated the 2_90 thermochromic. Because the difference from the rest isn't really significant, in terms of applicability costs it may be most affordable to chose the least amount of surface possible that in fact may have a difference in its capital cost and thus in its payback period.

It should be noted that although these cases were compared based strictly on performance of their natural characteristics, other factors will be important in determining which glazing technologies are appropriate. These factors include development and production costs, aesthetics appeal, durability and maintenance. Other important factors that could be considered along with this analysis is the incorporation of a ventilation system alongside heat recovery, as well as the implementation of a more efficient HVAC system that would replace the existing and rather old radiators with a more cost saving type. Such factors though are outside the scope of this report and they were not considered nor examined explicitly.

Experiments may give accurate results about its performance and reaction against solar radiation but in terms of a whole building, where multiple factors inter-react and have to be acknowledged, results may vary. Nevertheless, with the on-going monitoring, analysis and optimization of energy consumption, the building could be expected to meet very optimistic energy targets.

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8.1 Further work

This paper is an investigation of the possibilities available in applying thermochromic glass in public buildings. When analysing its use in Wates House it performed as expected. These results according to the research conducted, seem to improve when the thermochromic occupies more surface. Wates House is an ordinary office-type of building; therefore it is only logical to estimate that similar building types could benefit a great deal from such application.

As a result we are beginning to see many proposals speculating on how smart materials, like thermochromic, could begin to replace more conventional building materials. Cost and availability have, on the whole, restricted the replacement of conventional building materials with smart technologies. Smart systems are already in the market, like electrochromic or thermochromic glass. Pilkington is developing a solid state version of such glasses which should make it both cheaper and available in much larger sizes. This will dispense with the need for mechanical blinds and solar shades and will give individuals much greater control over their immediate environment. Another avant-garde technology with potential applicability in building facades is the 'Semi-Transparent Photovoltaic Module'[48]. This type of 'smart glass' is a self dimming, self powered glass that combines photovoltaic (PV) technology with electrochromic (EC) technology. It combines therefore the advantages of PV, by providing power to activate the EC layer, with the changeable properties of the electrochromic glass, which darkens or lightens the window.

Such glazing systems and technologies have great potentials. Their applicability can be widened and provide flexibility and savings in the design and construction not only of buildings, but these goals can be met in other sectors of the manufacture domain.

[48] www.rel.gov.com

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Appendix A

Building/Room type	Winter operative temp. range	Summer operative temp. range
Libraries:		
-lending/reference areas	19-21	21-23
-reading rooms	22-23	24-25
-store rooms	15	-
Offices:		
Executive/general	21-23	22-24
General building areas		
-corridors	19-21	21-23
-entrance halls/lobbies	19-21	21-23

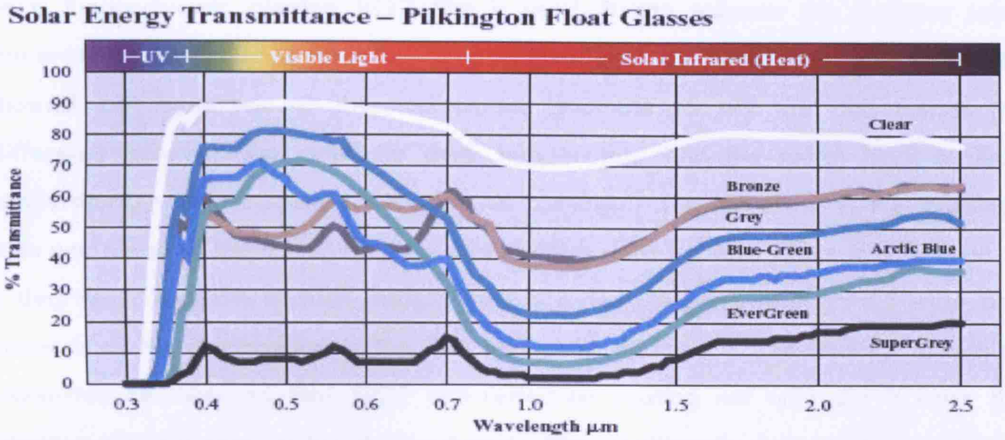
Table A1:Recommended comfort criteria for specific applications. Source Cibse Guide A, p.1-9

Building type	Use	Censity of occupation/person m^{-2}	Sensible heat gain/W.m^{-2} People	Lighting	Equipment	Latent heat gain/ Sensible heat gain/W.m^{-2}
Offices	General	12	6.7	8-12	15	5
		16	5	8-12	12	4
	City	6	12.5	8-12	25	10
	centre	10	8	8-12	18	6

Table A2: Benchmark allowances for internal heat gains in typical buildings. Source: Cibse Guide A

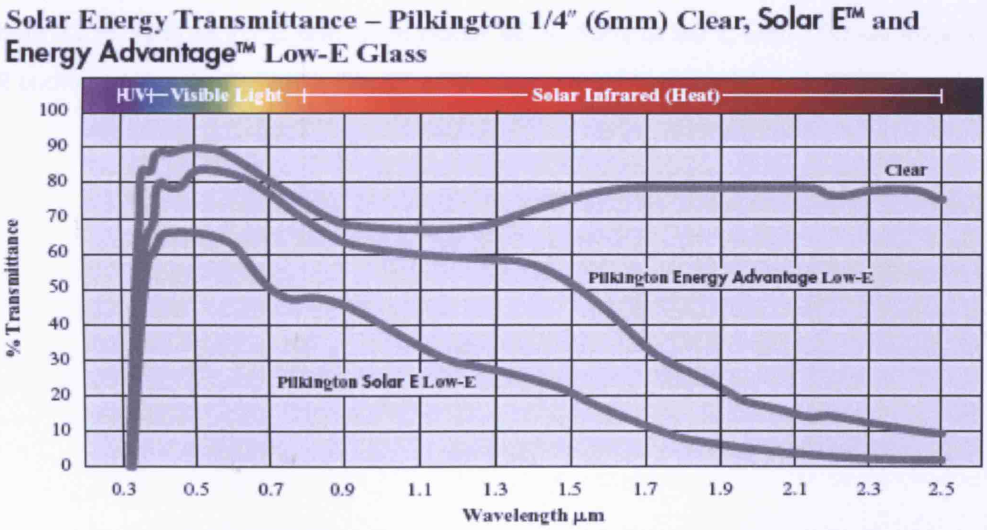
Appendix B

Solar Energy Transmittances of different types of glazing



Solar energy contains many different wavelength ranges of energy including ultraviolet (UV) radiation, visible light and infrared (IR) heat. A glazing needs to minimize UV radiation, because it causes about 60% of the fading and deterioration to interior furnishings. A glazing that allows high visible light transmittance will reduce the need for artificial light. And IR heat passage through a glazing is a major source of solar heat gain.

This chart shows what percent of each energy wavelength is transmitted through Pilkington 1/4" (6mm) monolithic float glasses. Most tinted glasses reduce the visible light and the infrared heat as a means of controlling solar heat gain. Pilkington **EverGreen™** Glass transmits more visible light than Grey or Bronze tinted glasses, yet blocks more of the I.R. heat and damaging UV rays. Pilkington **SuperGrey™** Glass combines exceptional control over solar heat gain with enhanced control over bright daylight and interior glare.



This graph shows how Pilkington **Solar E™** Solar Control Low-E Glass reduces solar heat gain by blocking most of the solar infrared wavelengths while still transmitting a high percentage of visible light. Pilkington **Energy Advantage™** Low-E, by contrast, transmits significantly more visible and infrared energy. This is the beneficial passive solar energy that it contributes to heating dominated climates. Clear glass, by comparison, transmits the most energy, but, lacking a low emissivity coating, it cannot reduce unwanted summer heat gain or costly winter nighttime heat loss.

Source: http://www.pilkington.com

Appendix C

Research conducted by Moon-Hee Lee in the Department of Electronic Materials Engineering of South Korea reference, showed that when an anti-reflection(AR) coating on a thermochromic glazing VO2 film is used, it can enhance the luminous solar transmittance of the glazing film. A report published by Babulanam and Granqvist showed that hysteresis of thermochromism (footnote to say that this means the difference between the switch to dark temperature and the switch back to light temperature) was broadened with the AR coating.[49] The hysteresis is the transition from one phase of the material to the other, which does not take place in a fraction of a degree. It requires a small margin that is a few degrees (e.g. ±4°C) wide and depends on the composition of the film and of its thickness[50]. The findings though of Moon-Hee Lee showed that SiO2 anti-reflection coating not only did it raise the luminous transmittance of the thermochromic film significantly both at low and high temperatures, it maintained as well its thermochromic properties. More specifically in an earlier investigation of the same department, AR deposition rate of 5 nm/s and the thickness of the AR coating between 100 and 300 nm were found to be adequate. They examined the luminous transmittances of the VO_2 films with and without AR coating at temperatures between 20 and 90°C in order to ascertain the AR effect of SiO_2 coating. The luminous transmittance at the wavelength of 650 nm increased from about 42 to 55% at 20°C and from about 40 to 50% at 90°C with 100 nm thick SiO_2 AR coating. More importantly the AR effect appeared both at 20 and 90°C.

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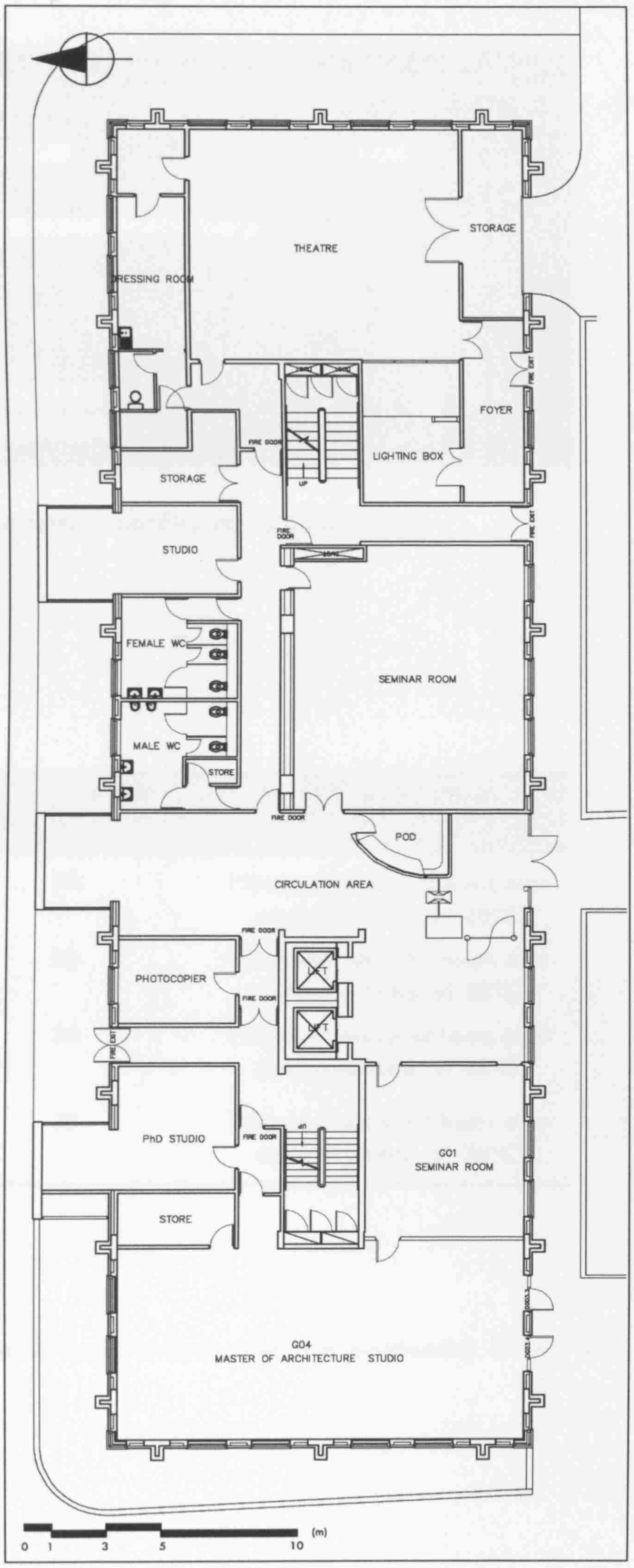
Appendix D

Ground Floor Plan of the existing building



Appendix E

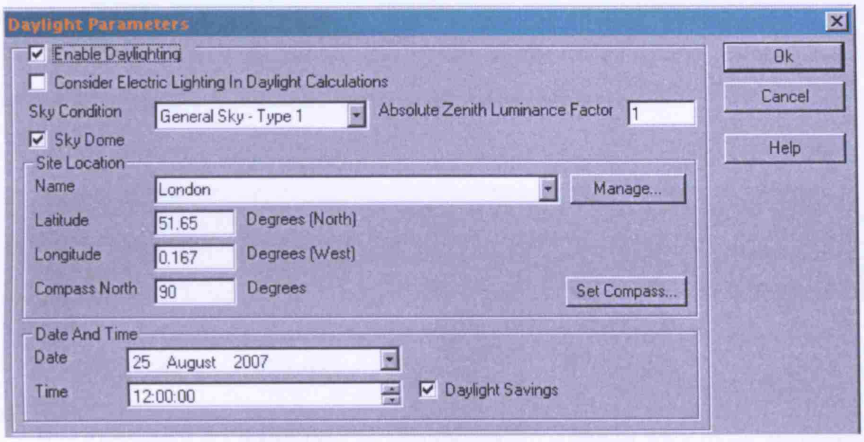


Figure C 1: Table of parameters regarding daylight calculations

Appendix F

Building	*Benchmark summer peak temp/ ℃*	*Overheating criterion*
Offices	28	1%annual occupied hours over operative temp. of 28°C
Schools	28	1%annual occupied hours over operative temp. of 28°C
Dwellings -living areas	28	1%annual occupied hours over operative temp. of 28°C
-bedrooms	28	1%annual occupied hours over operative temp. of 28°C

Table D 1: Benchmark summer peak temperatures and overheating criteria Source: CIBSE Guide A, p. 1.12

Appendix G

The following tables present the final results from the simulation procedure in TAS. All the estimated loads and costs for all the under study cases examined are summarized including the CO_2 emitted annually from each case respectively.

Case	Annual Energy Costs (£)				Total omprovement on the base case	% Energy saving
	Heating	Cooling	Lighting	Total		
Base case (1st Building)	10002.98	7622.89	20328.70	37954.57	0.00	0.00
1-Double glazing Low -E	2613.09	7430.90	19300.23	29344.22	8610.35	22.69
2-Thermochromic glass 30_60	1777.55	6955.49	16680.84	25413.88	12540.69	33.04
3-Thermochromic glass 2_0.90	1782.96	6601.85	16680.84	25065.65	12888.92	33.96
4- All thermochromic	1778.58	6141.43	17463.59	25383.60	12570.97	33.12

Table G 1: The annual energy costs for the base case model and all the tested versions of the thermochromic glazing

Case	Annual Loads (kWh/m²)				Total improvement on the base case
	Heating	Cooling	Lighting	Total	
Base case (1st Building)	22.54	17.18	45.81	85.54	0.00
1-Double glazing Low -E	5.36	15.25	39.61	60.22	17.67
2-Thermochromic glass 30_60	3.65	14.28	34.24	52.16	25.74
3-Thermochromic glass 2_0.90	3.66	13.55	34.24	51.44	26.45
4- All thermochromic	3.65	12.60	35.84	52.10	25.80

Table G 2: Annual loads for heating, cooling and lighting compared to the base case total loads required.

Case	Annual CO2 emissions (kg C/m²)				Total omprovement on the base case	% Energy saving
	Heating	Cooling	Lighting	Total		
Base case (1st Building)	2.86	2.18	5.82	10.86	0.00	0.00
1-Double glazing Low-E	0.68	1.94	5.03	7.65	3.21	29.59
2-Thermochromic glass 30_60	0.46	1.81	4.35	6.62	4.24	39.02
3-Thermochromic glass 2_90	0.46	1.72	4.35	6.53	4.33	39.86
4-All thermochromic	0.46	1.60	4.55	6.62	4.25	39.09

Table G 3: CO_2 emissions of each case study and their % emission savings.